Issue DOI: 10.61413/BMCV1428

ISSN 2664-5289

ELECTRO

SCIENTIFIC-INDUSTRIAL JOURNAL

ENERGETICS
TECHNICS
MECHANICS
+ CONTROL

Volume 13 No 2

BAKU 2023

Azerbaijan State Oil and Industrial University

Azerbaijan Scientific-Research & Design Prospecting Power Engineering Institute

Azerbaijan Technical University

ELECTROENERGETICS, ELECTROTECHNICS ELECTROMECHANICS + CONTROL

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Innovative Energy Systems: The Role of Energy 4.0 in Shaping Azerbaijan's Sector

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DOI - 10.61413/BYCI6990

Abstract. This article examines the transformation of the energy sector in the 21st century and its defining characteristics within the framework of the 2030 Sustainable Development Agenda. It analyzes the implications of contemporary advancements and advocates for the transition to the '3D' principles—Decentralization, Decarbonization, and Digitalization. This shift is supported by the increasing adoption of distributed generation and intelligent decentralized management systems. Furthermore, the article explores the integration of the Internet of Energy and Artificial Intelligence methodologies in the sector's next developmental phase, alongside the implementation of Web3 technologies. It also offers comprehensive recommendations for Azerbaijan's energy sector from 2021 to 2050, considering these evolving trends.

Keywords: Energy 4.0-Energy transformation, Renewable energy, Decarbonization, Digitalization, Decentralized intelligent management system, Blockchain, Artificial intelligence

1. İntroduction

From 2015 to 2021, global population access to electricity increased from 87% to 91%. The goal of ensuring universal access to affordable electricity by 2030 is pivotal. It involves investments in clean energy sources like solar, wind, and thermal, expansion of infrastructure, and technology upgrades to ensure clean energy in all developing countries. This goal is not only crucial for stimulating growth but also for environmental conservation.According to the United Nations Development Program's reports on Access to Electricity, several key points are noteworthy:

- The world is making progress towards sustainable energy targets, but not at a sufficient pace. If the current rate continues, approximately 660 million people will still lack access to electricity, and nearly 2 billion people will continue to rely on polluting fuels and technologies for cooking by 2030.
- Renewable sources account for nearly 30% of energy consumption in the electricity sector. However, challenges persist in the heating and transport sectors. Developing countries are experiencing a 9.6% annual growth in renewable energy installation, but international financial flows for clean energy are declining despite enormous needs.
- To achieve universal energy access by 2030, it is imperative to accelerate electrification, increase investments in renewable energy, improve energy efficiency, and develop enabling policies and regulatory frameworks.

- As of now, 733 million people, or about one in ten people worldwide, do not have access to electricity.
- The rate of electricity access has increased from 73% in 1998 to 90% in 2020.
- An estimated annual investment of between US$ 35 billion and 40 billion is required to achieve universal electricity access between 2021 and 2030.
- Despite the rise in global electricity access from 87% in 2015 to 91% in 2021, 675 million people, primarily in Least Developed Countries (LDCs) and sub-Saharan Africa, remain without access.
- While there has been progress in improving access to electricity and clean cooking fuels globally, 675 million people remain unconnected to grids, and 2.3 billion continue to rely on unsafe and polluting fuels for cooking.
- In 2021, 71% of the global population had access to clean cooking fuels and technologies, up from 64% in 2015. However, sub-Saharan Africa, the region with the lowest access rates, has seen a failure in progress towards clean cooking, failing to keep pace with growing populations, leaving a total of 0.9 billion people without access in 2021.

This essay will delve into these issues, exploring the challenges and potential solutions to achieving universal access to clean and affordable energy.

Considering the data previously mentioned, it becomes evident that the pursuit of sustainable energy objectives is underway in contemporary society. Nevertheless, the strides made thus far fall short of what is required. The bedrockof our everyday existence is the access to sustainable and economical energy sources. Yet, it is crucial to acknowledge that energy utilization significantly contributes to climate change, representing around 60% of the worldwide total greenhouse gas emissions

In 2015, the global community ratified a Sustainable Development Agenda projected through to 2030, encompassing 17 Sustainable Development Goals (SDGs). The fruition of these objectives is intricately linked to the provision of sustainable energy. Energy stands as a pivotal element in surmounting the myriad of challenges and seizing opportunities that our world encounters. The availability of energy is a cornerstone for employment, security, combating climate change, food production, and income enhancement. Sustainable energy presents a gateway to revolutionizing individual lives, economic landscapes, and environmental stewardship. The assurance of an effective and equitable working milieu, alongside balanced development in our quotidian routines, hinges on the dependability and affordability of energy services. A robust energy infrastructure underpins diverse sectors including commerce, healthcare, education, agriculture, infrastructure, communications, and advanced technology. Conversely, the absence of energy access poses a significant impediment to societal and economic progression.

Within the framework of these considerations, the seventh SDG underscores the imperative of granting universal access to affordable, reliable, sustainable, and contemporary energy solutions. In alignment with this goal, nations have formulated and implemented a variety of energy strategies. The ‘Sustainable Energy for All’ initiative, spearheaded by former UN Secretary-General Ban Ki-moon, endeavors to guarantee global access to modern energy amenities, augment efficiency, and amplify the adoption of alternative and renewable energy modalities. The principal tenets of this initiative are delineated in Table 1, showcasing the respective targets and indicators. [1,2]

Table 1. ‘’Ensure access to affordable, reliable, sustainable and modern energy for all’’ initiative targets and indicators

Goals 7. Ensure access to affordable, reliable, sustainable and modern energy for all	
Goals	Indicators
7.1. By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.1 Proportion of population with access to electricity 7.1.2 Proportion of population with primary reliance on clean fuels and technology
7.2. By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption
7.3. By 2030, double the global rate of improvement in energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP
7.a. By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology	7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems
7.b. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support	7.b.1 Installed renewable energy-generating capacity in developing and developed countries (in watts per capita)

Historically, the energy sector has undergone three significant transformations, with a fourth currently unfolding:

- The first energy transformation: Transition from biofuels such as wood and charcoal to coal, where coal’s contribution to primary energy surged from 5% in 1840 to 50% by 1900.
- The second energy transformation: A rise in oil’s share of primary energy from 3% in 1915 to 45% in 1975.
- The third energy transformation: An expansion in the utilization of natural gas, increasing from 3% in 1930 to 23% in 2017.

- The fourth energy transformation: A shift towards renewable energy sources like wind and solar, which accounted for 7.4% in 2019.

Each preceding energy transition was propelled by demographic expansion and the depletion of ecological niches, necessitating the creation of new domains and economic governance models. These shifts demanded a more efficient energy sector, leading to the dominance of new energy resources. Previous transitions facilitated the broadening of humanity’s ecological niche, the absolute enhancement of economic growth and productivity, and were linked with the advent of a diverse array of new production, transportation, and domestic technologies, as well as the establishment of novel social institutions.

The essence of the current energy sector transformation lies in phasing out hydrocarbon-based fuels from the energy mix, embracing the extensive use of renewable energy sources (RES), and advancing the electrification of various economic sectors.

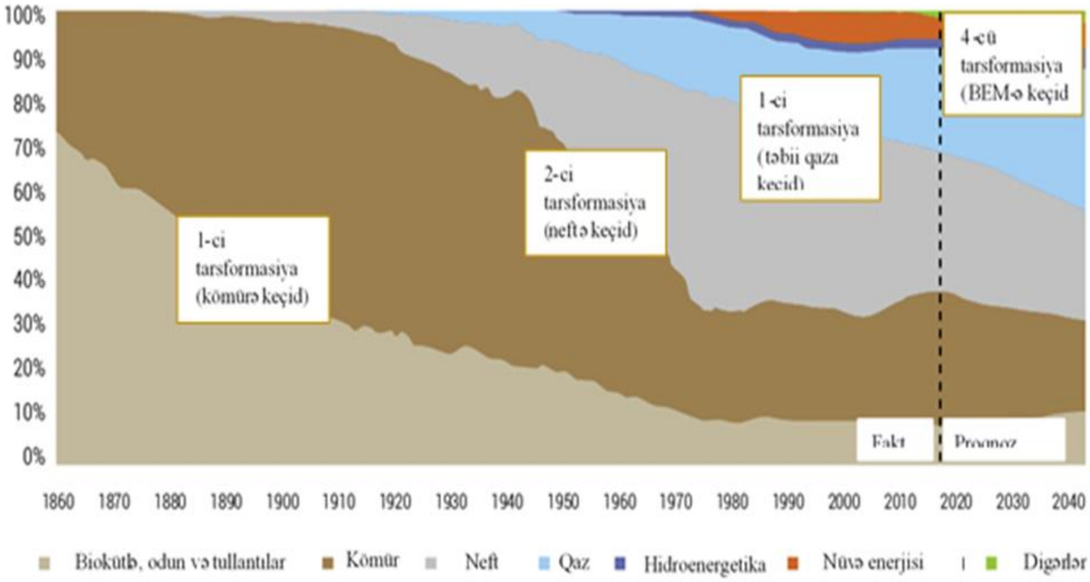

Figure 1 A retrospect of energy transformation

2. Scenarios of energy transformation in Azerbaijan

Azerbaijan, historically a beneficiary of the hydrocarbon economy and characterized by a modest level of innovation, has long approached the energy transformation process with prudence, adhering to a conservative policy in advancing other energy sectors. Presently, the acute nature of climate issues and global imperatives necessitates a comprehensive and forward-thinking response.

The ‘Long-Term Energy Strategy of Azerbaijan for 2021-2050,’ crafted by EXERGIA S.A. in June 2020 under the aegis of the Ministry of Energy of the Republic of Azerbaijan, delineates three distinct scenarios that reflect varying models of behavior:

- Base Scenario (BS): This scenario adopts a conservative stance on energy efficiency, renewable energy, and market restructuring initiatives, excluding the GHG emission benchmarks set forth in the UN Framework Document on Climate Change (Paris Agreement).
- Extended Climate Change Adaptation Scenario (IDUS): Building upon the Base Scenario, this model sets forth GHG emission targets for Azerbaijan for the years 2030 and 2050.

- Climate Change and High Growth Scenario (CHDIS): In addition to the IDUS parameters, this scenario anticipates accelerated economic growth.

Interventions identified for each energy sector within these scenarios include:

- Revamping the electricity market;
- Overhauling the gas market;
- Enhancing energy efficiency;
- Expanding renewable energy;
- Promoting Low Carbon Transport.

The strategic implementation of Azerbaijan’s energy sector transformation is structured into three principal phases:

- Phase 1: Capacity Building Period (2021-2023) – A phase dedicated to the Ministry of Energy’s development of capabilities to execute and oversee the strategy across all sectors, establishing the requisite institutional, legal, and regulatory frameworks.
- Phase 2: Rational Management Period (2023-2030) – A focus on the planned reform measures within Azerbaijan’s critical electricity, gas, and heating sectors.
- Phase 3: Full Adaptation Period to Reforms (2030-2050) – A period anticipated for the full execution of investment activities, particularly in renewable energy and low carbon emissions.

The trajectory of carbon emissions within the Azerbaijani energy sector by the conclusion of the second phase (2030) across all scenarios is depicted in Figure 4 [10].

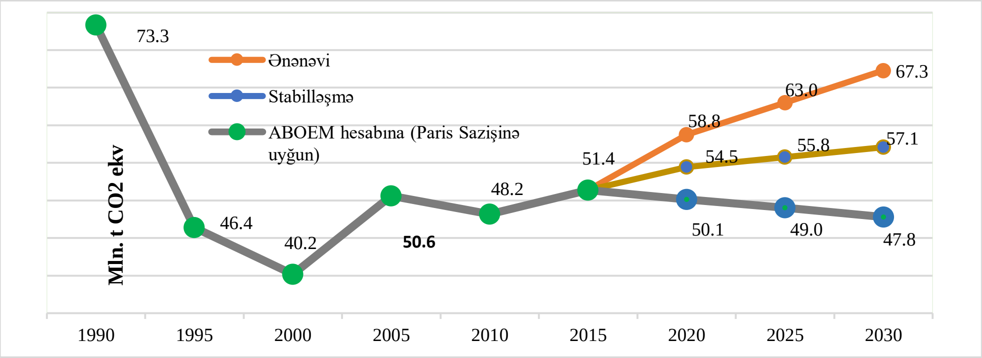

Figure 2. Dynamics of carbon emissions under different scenarios.

2. Problem Statement. Energy 4.0 Challenges of the next stage of development

The new industry 4.0 has brought many different approaches in the field of Energy as well as in many revolutionary fields. So, due to this, two more important trends in the field of energy have become widespread:

• decentralization and flexibility expressed by the large-scale development of distributed energy sources, the emergence of active consumers and

• digitization, which consists of the widespread use of digitally controlled devices connected to information networks.

Basically, the main principles of the latest energy transition are expressed by the 3D formula: decorbanization (decarbonization), decentralization (decentralization), digitalization (digitalization).

2.1 Decarbonization

The current phase of the energy transition is not solely a consequence of the depletion of humanity's ecological niche or a crisis within the prevailing economic model. It encompasses a broader consensus among experts and policymakers on the anthropogenic causes of climate warming, the European Union's intent to lessen its reliance on hydrocarbon-rich nations, and the aspirations of these nations' leaders to explore new sources of energy and economic growth. This phase also reflects the emergence of influential nations like China and India and the interplay of political interests.

The UN's 2021 Emissions Gap Report starkly notes that, despite national pledges to curtail GHG emissions and other climate mitigation efforts, the world is veering toward a 4°C rise in global temperatures by the century's end, leading to widespread and severe climate impacts. The report underscores the urgency to halve annual greenhouse gas emissions within the next eight years to maintain global warming below 1.5°C within our lifetime.

Furthermore, the International Energy Agency (IEA) posits that achieving net-zero emissions by 2050 requires more than technological solutions; it calls for profound behavioral changes, particularly in affluent nations where high energy consumption is synonymous with the standard of living.

Research into the economics of new energy and its influence on economic disparity is burgeoning. For instance, a study by the University of Aarhus, along with the Universities of Sussex and Manchester, indicates that Germany's shift to solar power generation has led to increased exploitation and environmental challenges in countries like Ghana and the Democratic Republic of Congo.

Hence, the trajectory of energy transformation, driven by decarbonization goals, stands in stark contrast to notions of social and economic advancement. In a world preoccupied with the threat of climate disasters, there's a risk that the global transformation of core infrastructure for new energy has commenced prematurely, without a clear vision for humanity's next developmental steps or a comprehensive consideration of new global and regional ramifications. This highlights the complexity of balancing immediate climate action with long-term sustainable development and equity. [5,6]

2.2 Decentralisation

In the current era, industries, small and medium enterprises (SMEs), and citizens are dependent on centralized markets and infrastructures for their energy needs. These pivotal players encounter challenges such as rising energy costs, the need to secure energy supply for consistent access, and the environmental burden of CO2 emissions.With the advancement and maturation of new energy technologies, many consumers have become producers, seeking greater control and contributing to increased system efficiency. This paradigm shift necessitates a more adaptable energy system capable of integrating new consumption and production nodes, thereby ensuring a sustainable and autonomous energy landscape. [7]

To foster the decentralization of energy, it is essential to embrace a suite of concepts that collectively facilitate the establishment of a system functioning as a coordinator for producers and consumers. This system should be governed by explicit regulations and transparent market operations. The goal of localized energy production is to forge systems that are more adaptable and robust, utilizing innovative methods to harness energy from diverse sources such as solar, wind, and biomass. These approaches aim to yield enhanced outcomes for all stakeholders, be it through diminished costs or heightened environmental sustainability. [7,8]

Despite the shift towards decentralization, it is crucial to ensure that existing entities within the energy framework remain central to the new paradigm due to the intricate nature of the system, particularly the necessity for electrical grid interconnections. Therefore, the distribution system operator (DSO) and energy traders are fundamental to this transition. [7,9]

Blockchain networks serve to bolster the integrity and transparency of the entire process, safeguarding transactions. The security of the network is contingent upon the consensus mechanism employed, requiring substantial support from the network to authorize changes. Beyond security, the deployment of blockchain technology offers numerous additional benefits that can aid in the execution of a local energy production system, enhancing efficiency and trust among participants. [7,9]

In the realm of traditional energy markets, transactions were predominantly conducted through a centralized model, involving multiple intermediaries. This model aligns with the conventional operations of the electricity grid, a practice that persists to this day. However, the shift towards alternative energy sources necessitates the adoption of novel models that are more attuned to the evolving demands of burgeoning urban centers, characterized by changes in energy consumption patterns and demographic growth.In a centralized system, the financial burdens and concerns regarding the security of supply are accentuated. In contrast, decentralized models have demonstrated the potential to enhance performance and efficiency by approximately 40% when compared to their centralized counterparts. This significant improvement underscores the need for a thorough examination of how electricity markets function, including their regulatory frameworks and key stakeholders. Such an analysis is crucial to determine the feasibility of implementing microgrid energy solutions on a smaller scale, which could offer more localized, efficient, and resilient energy distribution systems [7]

The electricity markets of today are characterized by their intricate and dynamic nature, encompassing a multitude of roles from generation to commercialization. For a company or organization to engage in energy sales, it must establish itself as an energy seller, a requirement that poses a significant hurdle for small-scale prosumers who both produce and consume energy. [7]

At the European level, the European Commission has enacted directives 2018/2201[8] and 2019/944[9] to facilitate the formation of energy communities and encourage the shift towards decentralized energy systems. These directives aim to streamline government processes and reduce the legislative burden on local energy production. The Joint Research Center’s report “Energy Communities: an overview of energy and social innovation” highlights the role of economic factors, such as income levels and the capacity to acquire renewable installations, in the development of energy communities. The report notes a marked disparity in the adoption of such technologies across Southern, Central, and Eastern Europe since 2000, underscoring the need for equitable conditions that allow all initiatives to compete fairly in the market.A key benefit of energy decentralization is the potential reduction in environmental issues and energy losses. By increasing the proportion of renewable energy sources within the electricity grid, particularly at points close to energy consumption, the need for extensive transmission or distribution networks is diminished. This proximity between production and consumption not only enhances efficiency but also contributes to a more sustainable energy ecosystem [7].

Table 2. Differences between centralized and decentralized trading

Description	Centralized Trading	Decentralized Trading
Regulator [17]	Centralized regulator (one entity) with common rules.	Possible to implement specific regulations for an energy renewable community.
Energy Distribution [18]	Centralized, managed by one entity.	Possible to decentralize, building an internal distribution electrical power grid, maintained by the entity that manages de community.
Primary Energy Supplier [13]	Large scale generators.	Prosumers with renewable energy systems.
Trading [13]	Central markets, fixed price tariffs.	Bidding prices or prices according to usage factor.
Contract type [19]	General contract for low voltage clients based on legislation. National regulators provide standard contractual clauses that must be complied with by all suppliers.	Standardized smart contract with rules defined by the entity that manages the community.
Management [20]	Third party, smart meter. Operations are carried out by network, transmission and distribution operators.	Smart meter and smart contract, energy management system. All this information is stored on the network for all actors to analyze.
Policy and network changes [17]	Policy maker, national action plans, legislation.	Consensus of network participants.

Peer-to-peer (P2P) transactions and decentralized energy production represent a significant shift in the energy market, enabling individuals who generate power—such as through solar photovoltaic systems—to sell surplus energy locally and securely. This model has the potential to revolutionize the market. Nonetheless, it is subject to regulatory frameworks that vary by country and must be adhered to. In the absence of a dedicated energy distribution grid between producer and consumer, energy must be injected into the main grid, necessitating distributor authorization and compliance with legislative procedures. Alternatively, traders can purchase this energy and resell it at market rates, but third-party involvement typically leads to higher prices. [7]

The rise in decentralized installations introduces challenges of intermittency. Existing distribution networks were not designed to handle excess production, leading to disruptions and additional management costs for maintaining network balance. Entities may need to expand grid capacity to manage this, incurring further costs. Therefore, demand/response mitigation strategies and consumer incentives are crucial. Additionally, the variability of solar and wind energy production due to weather conditions necessitates robust control systems to manage potential surpluses, particularly for local grids serving households. This highlights the complexity of integrating decentralized energy sources into existing infrastructures and the importance of developing adaptive management and regulatory approaches [20].

By adding a larger number of installations at the community and neighborhood level, the complexity is increased; however, it also allows the management to be carried out with a greater number of equipment, thus allowing a more complex electrical power grid management. More installations in the electrical power grid have the advantage of reducing losses in the electrical power grid, since production is local and does not need to use the transmission electrical power grid. One of the proposals made to solve some of these problems is to convert the generated energy into a virtual currency, thus allowing the settlement between the various actors [13]. The Ethereum framework, for example, uses the concept of "gas" payments for smart contracts and transactions, where "gas" corresponds to a metric of the computational effort for the operations. The virtual coin used in this case is the Ethereum token ether, and all smart contracts work based on this [16]. One ether corresponded to 1964.32 according to Coinbase as of 7 July 2021.

Blockchain can be a powerful tool to help to implement microgrid solutions to provide robust and secure transactions and data exchange between all actors of the process, in order to promote energy decentralization [21,22,23]. Table 1 presents the main differences between the centralized trading approach used with energy companies and the proposed peer-to-peer trading approach [17].

The concept presented in Figure 9 is indeed reflective of the evolving landscape in energy trading platforms. The integration of peer-to-peer (P2P) and blockchain technologies signifies a shift towards a more decentralized model of energy distribution and trading. Despite this decentralization, the role of the Distribution System Operator (DSO) remains crucial. The DSO is responsible for maintaining the balance of the network and managing the electrical power grid connections, which are essential for the overall stability and reliability of the power system.

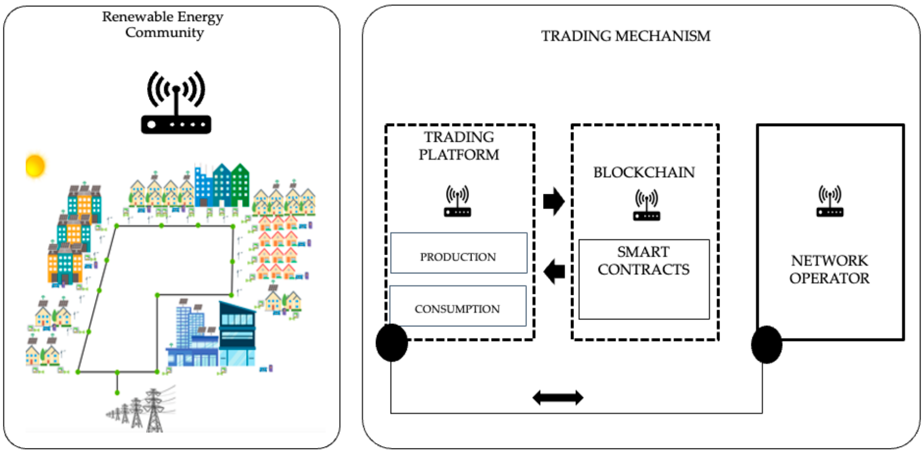

Figure 3. Peer-to-peer (P2P) trading platform concept

The DSO's involvement ensures that, while the trading platform operates on a decentralized framework, there is still a centralized authority overseeing the critical aspects of energy distribution. This dual approach leverages the benefits of a decentralized system—such as increased efficiency, transparency, and user empowerment—while maintaining the necessary oversight to ensure network stability and continuity of service12.

The DSO's role in such a decentralized energy landscape includes connecting renewables, enabling flexibility, supporting electrification, and empowering consumers to engage actively in the energy market2. As the energy sector continues to evolve, the DSO’s functions will adapt to accommodate new technologies and market structures, ensuring a secure and efficient energy supply

2.3 Digitization

In contemporary electric power systems, ensuring stability necessitates persistent monitoring and comprehensive data analysis. The formulation of strategic action plans to prevent recurrent issues is paramount. The advent of scientific innovations, particularly in artificial intelligence (AI), has revolutionized data analysis, decision-making processes, and even the implementation of decisions.

Data acquisition from users, as depicted in Figure 5, is executed through smart devices and concentrators based on the Internet of Things (IoT) paradigm, forming the system’s infrastructure. The embedded system user interface processes data in situ, and connectivity to mobile and internet networks is facilitated via the IPv6 protocol. The data lifecycle, encompassing collection, processing, and storage, is managed through machine learning techniques, while advanced AI methods such as Deep Learning—encompassing neural networks, genetic algorithms, multi-agent systems, fuzzy theory, etc.—are employed for extensive application. This process generates a substantial dataset, termed Big Data, which enhances decision-making and management capabilities for users.

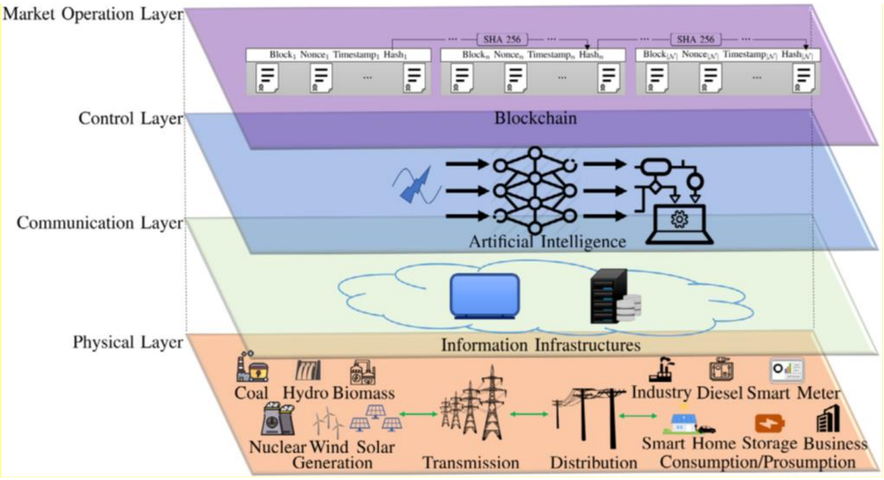

Figure 3 The Topology of Decentralized managment system

Contemporary scholarly inquiries into Big Data’s application within the modern energy sector predominantly traverse the subsequent trajectories;

-Energy Asset
-Operation Managment
-Demand -Response Managment(DRM)
-Fault Managment
-Predictive maintenance and monitoring
-Power quality analysıs
-Energy and load forecasting
-Parallel processing
-Cloud data mining

The most important of the issues raised in these directions is establishing the interaction of these data and systems. Therefore, it is very important to understand how to integrate them. During the integration, data uniformity, cyber security issues and long-term planning are important. attention should be paid. Big Data systems such as Apache Hadoop and MapReduce, Apache Spark and NoSQL technologies can be implemented. In addition, in the application of these solutions, IBM, Microsoft, SAP SE, Dell Technologies Inc., Accenture PLC, Infosys Limited, Intel Corporation, Schneider-Electric, Siemens Solutions offered by AG companies also play an important role.

For the application of Big data, which occupies such an important place in microgrid network systems, the transition to advanced digital technology (advanced digital technology) is inevitable and important. Especially with the introduction of IOT devices that can be connected to the Internet, qu occupies an important place among these technologies.

A single and collobarative platform Smart Grid System has been developed that connects devices based on the IoT platform through Edge Control, extracting real-time data and instant values to the Cloud for the application and iterative training of artificial intelligence technologies and analytics. The IoT platform is divided into 4 main components:

1.Collection: A common semantic structure and compatibility between all parts of the network is needed to provide facilities for transferring data and a framework for transferring said data.

2.Storage: Collected data should be stored in data storage, storage center should be organized and processed.

3.Processing: Raw data must be processed before it can be used. There must be a component that manages this, paradigms or implementations that can be implemented by any computational means.

4.Visualization : It should ensure that data is displayed to interested parties through graphs, dashboards, trends, tables and other tools.

3. Problem solving methods and approval.

3.1. Smart Grid -Advanced Distrubution Managment System

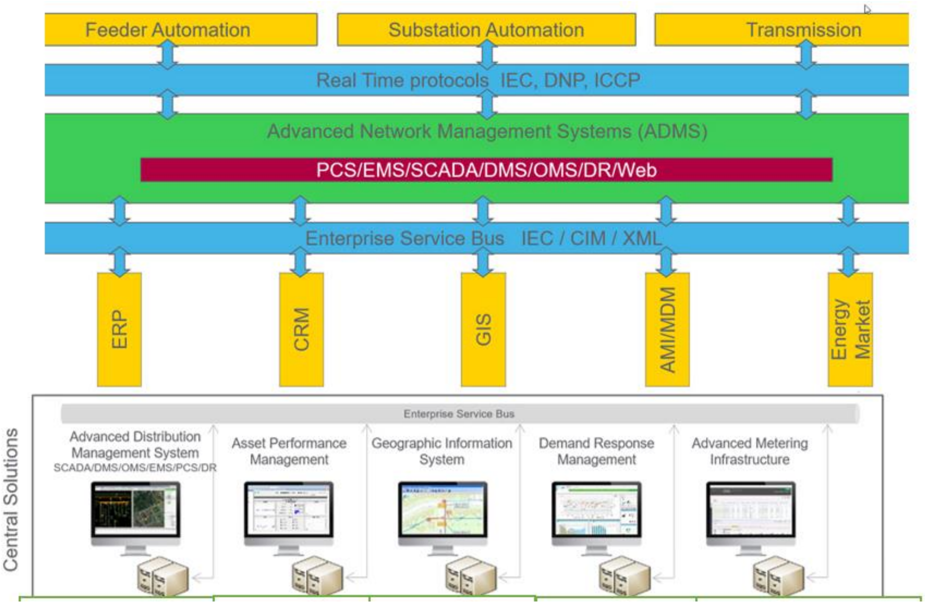
Feeder Automation
Substation Automation
Transmission
Real Time protocols IEC, DNP, ICCP
Advanced Network Management Systems (ADMS)
PCS/EMS/SCADA/DMS/OMS/DR/Web
Enterprise Service Bus IEC / CIM / XML
ERP
CRM
GIS
AMI/MDM
Energy Market
Central Solutions
Enterprise Service Bus
Advanced Distribution Management System
SCADA/DMS/OMS/EMS/PCS/DR
Asset Performance Management
Geographic Information System
Demand Response Management
Advanced Metering Infrastructure

Fıgure 4. System Topology of ADMS [13]

The adoption of a single system by the prominent manufacturers in Europe and globally, as illustrated in Figure 8 showcasing the topological structure, architecture, and software of Smart Grid systems, revolves around the central Advanced Distribution Management System (ADMS) supported by four essential auxiliary systems, collectively forming the sub-infrastructure of the overall system

3.2. AI application

Since 2011, Industry 4.0, also known as the Fourth Industrial Revolution, has captured the attention of many developed industrial countries worldwide. This transformative era presents significant opportunities for the application of revolutionary Artificial Intelligence (AI). Key technologies driving this revolution include the Internet of Things (IoT), advanced databases (Big Data), and cloud computing. Notably, AI, machine learning, and deep learning are essential components of the database, converging to create an intelligent system akin to human cognition. Moreover, countries across the globe are heavily investing in artificial intelligence, leading to a surge in patent applications and related activities in this field. [12].

As for Table 2, it outlines the functions of the four levels within the Smart Grid network model, highlighting the integral role of artificial intelligence methods in providing these functions. [21,22,23].

Table 3. AI application for Smart Grid [12].

Software	Abbreviation	Functions	AI Method
Advanced Distrubution System	ADMS	Optimization	Expert System
		Planning	Intelligent Tutoring
		Modernization	Systems
		Supervision	Evolutionary algorithm
		Selection,	Genetyc Algorithms
		Classification,	Maşın Öyrənməsi
		Evoluation,	Deep learning
		Forecast and Prediction	Adaptive Neuro-Fuzzy Inference System (ANFIS) + Fuzzy Logic Fuzzy Q-Learning
Asset Performance Management[24].	APM	Monitoring of Equipment Status	ANNs, Cluster analysis, Decision trees,

			Evolutionary (genetic) algorithms, LASSO regression, SVMs, NLP
Geographic İnformation System [23].	GİS	Geographical assignment	Data cleansing Image interpretation Semantic classification and segmentation Digital mapping
Demand Response Management	DRM	Forecasting Planning	Swarm Intelligence Game Theory Clustering Regression
Advanced Metering İnfrastructure	AMİ	Metering	Fuzzy Logic Ant Colony Bee Colony

Conculision

The dispersed topology of Microgrid Energy systems, coupled with the dynamic interactions among energy producers and consumers, necessitates the adoption of advanced digital technologies and artificial intelligence (AI), machine learning (ML), and deep learning (DL) algorithms. These technologies play a crucial role in addressing decision-making challenges. Research in this field has yielded several key findings:

- Enhanced Interaction: AI and Smart Grid systems facilitate interaction between critical infrastructures and various system users, including consumers, energy producers, designers, technical staff, and energy market analysts .
- Efficient Services: By organizing services for electric network equipment at optimal times and locations, AI-driven solutions streamline investment decisions .
- Accident Detection and Recovery: AI aids in early accident detection and enables swift response during recovery operations .

- Energy Supply Efficiency: Technological systems leveraging AI, ML, and DL methods are effective tools for improving energy supply efficiency in Microgrid networks, especially considering their probabilistic and dynamic nature .
- Tariff Determination and Regulation: Emerging technologies like blockchain and cryptocurrency can be harnessed to determine energy tariffs and regulate relations between energy producers and consumers based on supply and demand norms .

In the context of Azerbaijan’s energy sector, as a participant in the global market, careful consideration of modern energy approaches—particularly the Energy 4.0 paradigm—is essential during energy trade reforms and policy adoption

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INTELLIGENT CONTROL OF REACTIVE POWER FLOWS IN POWER DISTRIBUTION NETWORKS, TAKING INTO ACCOUNT THE INFLUENCE OF SPECIFIC LOADS

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DOI - 10.61413/IMJE6390

With the expanded use of distorting specific loads, it becomes relevant to address the issues of reducing their impact on the supply network, primarily on means of compensating reactive power flows. In order to obtain the necessary information to solve the issue of intelligent control of reactive power flows through electrical distribution networks (EDN) and for practical implementation, calculations of the higher harmonic components of currents and voltages were carried out using a real diagram of the EDN of the power system. An algorithm for intelligent control based on the theory of fuzzy logic for a static capacitor bank in a distribution network with a nonlinear load has been developed. The algorithm was simulated in MATLAB and practical calculation results were obtained. The results obtained showed the effectiveness of the developed algorithm. The voltage profile of the nodes of the real distribution network of the power system has been improved and active power losses have been significantly reduced.

Key words: power system, voltage profile, reactive power compensation, electrical distribution network, fuzzy logic, active power losses, membership function.

ENERJİSİSTEMİN PAYLAYICI ELEKTRİK ŞƏBƏKƏLƏRİ ÜZRƏ SPESİFİK TƏSİRLİ YÜKLƏRİ NƏZƏRƏ ALMAQLA REAKTİV GÜC AXINLARININ İNTELLEKTUAL İDARƏ OLUNMASI

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Təhrifedici spesifik yüklərin geniş tətbiqi onların qidalandırıcı şəbəkəyə, ilk növbədə reaktiv güc axınlarının kompensasiya vasitələrinə təsirinin azaldılması məsələsinin həllinin zəruriliyini aktuallaşdırır. Qidalandırıcı gərginliyin qeyri-sinusoidallığı şəraitində paylayıcı elektrik şəbəkələri (PEŞ) üzrə reaktiv güc axınlarının intellektual idarə məsələlərinin həlli üçün zəruri informasiyaların əldə olunması və praktik realizasiyası məqsədilə enerjisistemin real PEŞ sxemi üzrə gərginlik və cərəyanın yüksək harmonikalarının hesabatı aparılmışdır. Bundan sonra qeyri-xətti tələbatçıları olan PEŞ-də statik kondensator batareyalarının (SKB) qeyri-səlis məntiq nəzəriyyəsi əsasında intellektual idarə alqoritmi işlənmişdir. MATLAB mühitində alqoritmin modelləşdirilməsi yerinə yetirilmiş və praktik hesabat nəticələri alınmışdır. Alınmış nəticələr alqoritmin effektivliyini göstərmişdir. PEŞ düyünləri üzrə gərginliyin profili yaxşılaşmış və aktiv güc itkisi əhəmiyyətli dərəcədə azalmışdır.

Açar sözlər: enerjisistem, gərginliyin profili, reaktiv gücün kompensasiyası, paylayıcı elektrik şəbəkəsi, qeyri-səlis məntiq, aktiv güc itkisi, mənsubiyyət funksiyası.

ИНТЕЛЛЕКТУАЛЬНОЕ УПРАВЛЕНИЕ ПОТОКОВ РЕАКТИВНОЙ МОЩНОСТИ В РАСПРЕДЕЛИТЕЛЬНЫХ СЕТЯХ ЭНЕРГОСИСТЕМЫ С УЧЕТОМ ВЛИЯНИЕ СПЕЦИФИЧЕСКИХ НАГРУЗОК

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С расширенным применением искажающих специфических нагрузок становится актуальным решение вопросов уменьшения их влияния на питающую сеть, в первой очереди на средства компенсаций потоков реактивной мощности. В целях получения необходимой информации для решения вопроса интеллектуального управления потоков реактивной мощности по распределительным электрическим сетям (РЭС) и для практической реализации проведены расчеты высших гармонических составляющих токов и напряжений по реальной схеме РЭС энергосистемы. Разработан алгоритм интеллектуального управления на основе теории нечеткой логики статической конденсаторной батареей в РЭС с нелинейной нагрузкой. Выполнено моделирование алгоритма в среде MATLAB и получены практические результаты расчета. Полученные результаты показали эффективность разработанного алгоритма. По узлам реальной распределительной сети энергосистемы улучшен профил напряжения и в значительной степени уменьшились потери активной мощности.

Ключевые слова: энергосистем, профил напряжения, компенсация реактивной мощности, распределительная электрическая сеть, нечеткая логика, потери активной мощности, функция принадлежности.

INTRODUCTION

Economical use of all types of energy, including electricity, is one of the important state problems. As a special type of product, electricity has certain characteristics that allow us to determine its suitability for use in various production processes. A set of such characteristics is united around the concept of power quality. One of the main problems related to the improvement of the quality of electric power in both the design and operation stages of electric networks is the issue of reactive power compensation, which includes issues such as the selection of appropriate sources, the selection of their powers and regulation laws, and the optimal placement of reactive power sources.

Rational (optimal) compensation of reactive power in distribution power networks includes a wide range of complex issues aimed at increasing the efficiency of operation of electrical devices, improving the quality of electric power, and as a result of its implementation, reduction of losses caused by reactive power flows, stabilization of the voltage level at power network nodes due to regulation, high efficiency of electrical devices working with technical and economic indicators is ensured.

The problem of reactive power compensation (RPC) in electric networks remains relevant for the following reasons:

- the demand for reactive power in relation to active power in industrial areas has a preemptive increase;

- reactive power demand has a high growth rate due to the wide application rate of modern household loads in city electric networks;
- Reactive power demand in rural power grids also has an increasing growth rate.

Quantitative and qualitative changes in industries in recent years have given special importance to this issue. In the current period, the growth of reactive power demand significantly exceeds the growth of active power demand. In this case, the transfer of reactive power from the place of generation to the place of demand leads to the deterioration of technical and economic indicators of the electric network enterprise. There are big differences between reactive and active power from the point of view of production and consumption. Most of the active power is consumed by operators, only a small part is lost in network elements and electrical equipment. The reactive power loss in network elements is comparable to the level of reactive power required by operators. 22% of the 100% reactive power produced in the power system is lost in step-up transformers of the power station and 110-500kV autotransformers, 6.5% in district grid lines, 13.5% in step-down transformers, and only 58% of the produced reactive power -i enters the 6-10kV consumer buses [1, 2].

Intensification of production processes, increase of labor productivity is closely related to improvement of existing technologies and introduction of new advanced technologies. This includes the application of powerful valve converters, arc and induction electric furnaces, welding devices and other specific load devices that, despite all their technological effectiveness, have a negative impact on the quality indicators of electric power in electric networks.

It should be noted that practically all the quality indicators of electric energy in terms of voltage depend on the reactive power demand of operators. Therefore, the issue of the quality of electricity should be considered in direct connection with the issue of reactive power compensation. The problem can be solved by the synthesis and application of fast-acting multifunctional compensation of reactive power, which improves the quality of electric power in several parameters at the same time.

1. CHARACTERISTICS OF REACTIVE POWER COMPENSATION UNDER SPECIFIC LOAD APPLICATION CONDITIONS

The wide application of specific loads (non-linear, non-symmetrical, sharp change) in industrial areas makes it urgent to solve the issue of reducing their impact on the power supply network, first of all, on compensation means of reactive power flows.

It is known that the most convenient tool for reactive power compensation in distribution networks is the application of static capacitor batteries (SCB) [3-5]. This is due to their following advantages compared to other compensation means: the possibility of application at both low and high voltages; small active power losses - (0.0025 - 0.005 kW/kVAr); the lowest specific cost (per 1 kVAr) compared to other compensating devices; simplicity of operation (absence of rotating and moving parts); simplicity of installation works (small mass, no foundation required), etc. In addition, the application of conventional reactive power compensation (RPC) means calculated for sinusoidal voltage and current in networks with high harmonic components of voltage and current generated by non-linear loads is related to certain technical difficulties. Capacitors operating under non-sinusoidal voltage conditions fail quickly, with explosions and blistering observed in some cases. The main reason for failure of capacitors is their overloading with high harmonic currents, which, as a rule, is caused by the fact that SCB changes the frequency characteristic of the system and causes current resonance. When SCB is connected to substation buses feeding large valve loads, regardless of its capacity, such a group of harmonics is found that the capacitors enter the current resonance mode (or close to it) with the inductance of the network.

Resonance harmonic group currents generated by nonlinear voltamper characteristic operators to the network increase significantly, and it can be noted that the voltage of these harmonics is directly applied to SKB. In addition, the capacitance resistance of SCB decreases as the number of harmonics increases. This leads to the fact that resonant currents of the same size as the first harmonic, and sometimes more, flow through the SCB. Capacitors can be overcharged up to 30% for current and 10% for voltage. In fact, the current overload due to resonance can reach 400-500%, so that the resonant frequency currents can significantly exceed the first harmonic current. When choosing the power of the SCB and the installation location, it is necessary to take into account the possibility of a resonance phenomenon occurring in one of the harmonic voltage and current frequencies generated by the non-linear loads. For example, for the purpose of reactive power compensation, SCB with a total capacity of 11500 kVAr was installed in one of the industrial enterprises. However, due to the high harmonics generated by the semiconductor rectifier units, it was not possible to connect them. The increase of sudden current surges to 150-180% caused the failure of capacitors: 50 capacitor banks with a total capacity of 1400kVAr failed in 5 hours. Abnormal "humming" of SCB and its opening from maximum protection were observed. At the same time, it should be noted that the normal operation of the device is impossible without compensating the reactive power, because it is the power factor [6-8].

In conditions of non-sinusoidal voltage, it is necessary to look at the operation of SCB from the point of view of the interaction of the high harmonics of the supply network and capacitor batteries. Numerous experiments have shown that the voltage non-sinusoidality in the distribution networks fed by the draft substations with valve converters, as a rule, exceeds the standards set by the standard [9], and in some cases reaches 20%. Therefore, the issue of RPC in the mentioned nonlinear load networks has not yet been fully resolved.

The report of power grids with valve inverters showed that when connecting SCB for the purpose of RPC, its current exceeds the required norm many times, which leads to damage of capacitors. The final harmonic coefficient increases sharply at the point where the SCB is connected. Figure 1 shows the scheme of the distribution network feeding the thyristor converter. Condenser unit for RPC is stacked.

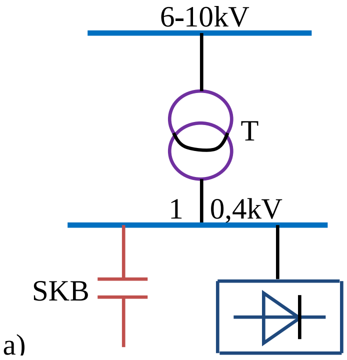


Figure 1. Connection scheme of SCB to the converter

Figure 2 shows the oscillograms of the supply network voltage and the current of the SCB connected to the valve load for RPC. For the case of C=70μF, the values of harmonic currents of

SCB were obtained as follows: I1=100%, I7=90%, I5=160%, I7=60%. The capacitor current overload is 200%, the final harmonic sum factor.

Thus, it is a problem to use SCBs for the purpose of RPC in specific load networks. In each specific case, it is required to report the overcharging of the battery with resonant group harmonics. In some cases, especially when the capacity of the SCB is small, such reports should be made up to harmonics of a fairly high order [9].

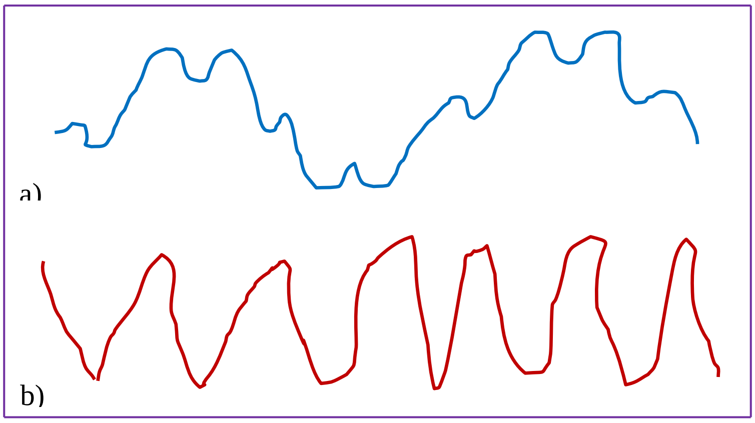


Figure 2. Oscillograms obtained in the physical model (Figure 1).
a - phase voltage at point 1; b - current in SCB (C=70µF)

2. CALCULATION OF NON-SINUSOIDAL INDICATORS ON STANDARD AND REAL NETWORK SCHEMES

In order to develop the intelligent management algorithm of SCB under specific load conditions, the report of the high harmonics of the voltage in the tires and the current in the branches was carried out according to the 14-node standard IEEE scheme and the real EDH scheme of the power system.

In a 14-node circuit, a high harmonic source (HHS) consisting of a 6-phase rectifier is connected to two buses in ETAP format. For the case with HHM on bus 4, the reported results of voltage final harmonic ratio (THD) for buses B1-B4 and B14 are shown in figure 3. As can be seen from the figure, the ratio of the voltage to the final harmonic complex is equal to 7% in the B4 bus at the maximum value of the load, which is more than the norm according to [10-15]. In other tires, the coefficient is within the normal limits.

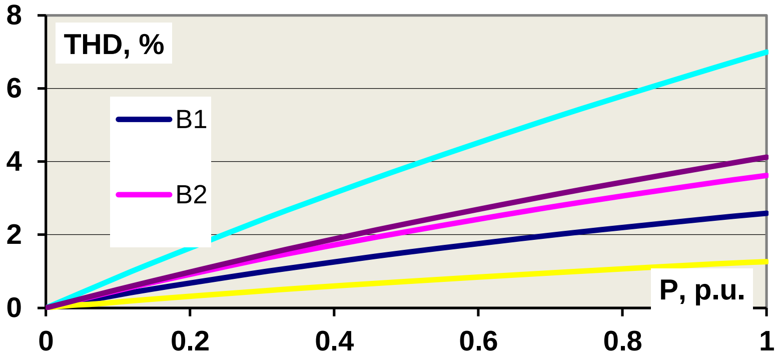


Figure 3. The source of THD for the case of connecting HHS to B4 power-dependent variation curves

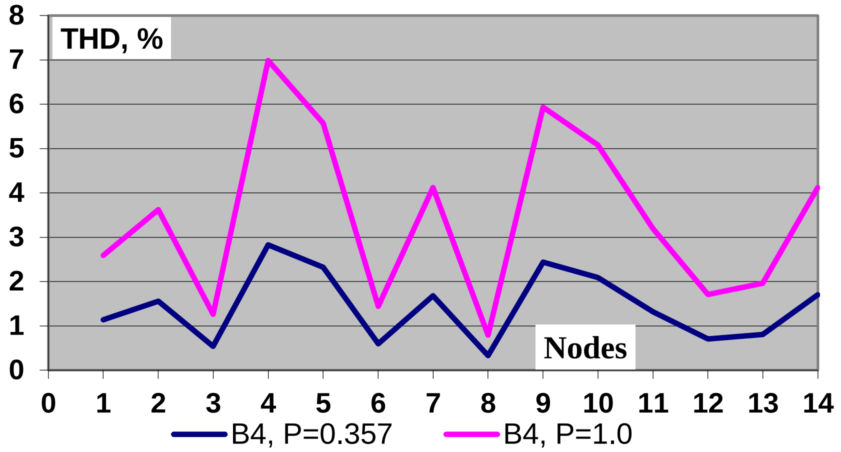


Figure 4. Profile of THD for two values of power of HHS connected to B4

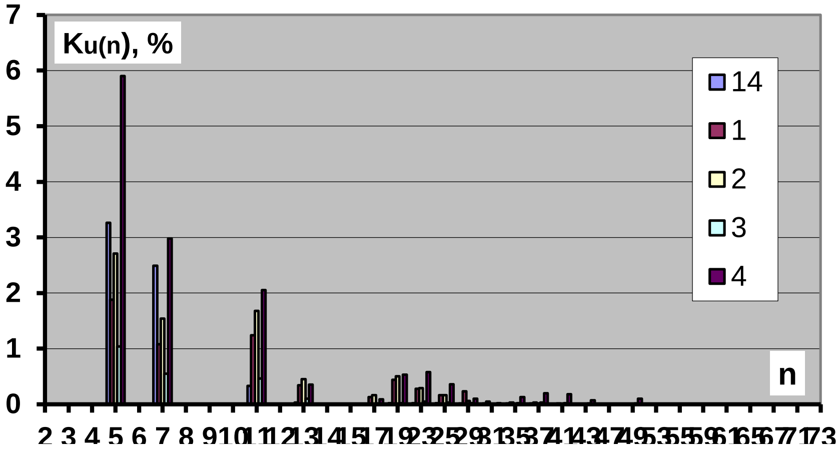


Figure 5. Spectral composition of the voltage for the case of connecting HHS to node B4
a-B1 tire; b-B2 tire; c-B3 tire; d-B4 tire; e-B14 tire; e-summary

Figure 4 shows the profiles of the coefficient of the HHS power for two values of the B4 bus. P=0.357 n.v. values of the coefficient are within the norm in all tires. In the case of P=1.0, in some nodes, for example, 7% is obtained in the B4 node, and close to 6% in the B5 and B9 nodes.

For the case considered in Figure 5, the spectra of the voltage on the B1-B4 and B14 tires are depicted. As can be seen, the spectrum is dominated by the 5th, 7th, 11th, 13th and sometimes the 23rd harmonics.

3. REPORT ON THE REAL NETWORKS OF THE ENERGY SYSTEM

For the purpose of development and practical implementation of the intelligent control algorithm of SCB in the non-sinusoidal condition of the voltage, the report of the high harmonics of the voltage in the tires and the current in the branches was made according to the real EDH scheme of the energy system. The reports were made for the 110/35/10 kV grid circuit fragment of the power system shown in Figure 6. Musulli, Ujar and Leki DYSs are connected to the scheme from the 110kV side. These converter substations send high harmonics into the grid, significantly degrading the quality of electricity. Considering this, the study of high harmonics of voltage and current is considered in order to implement an effective solution to the problem of reactive power compensation and its control in these networks.

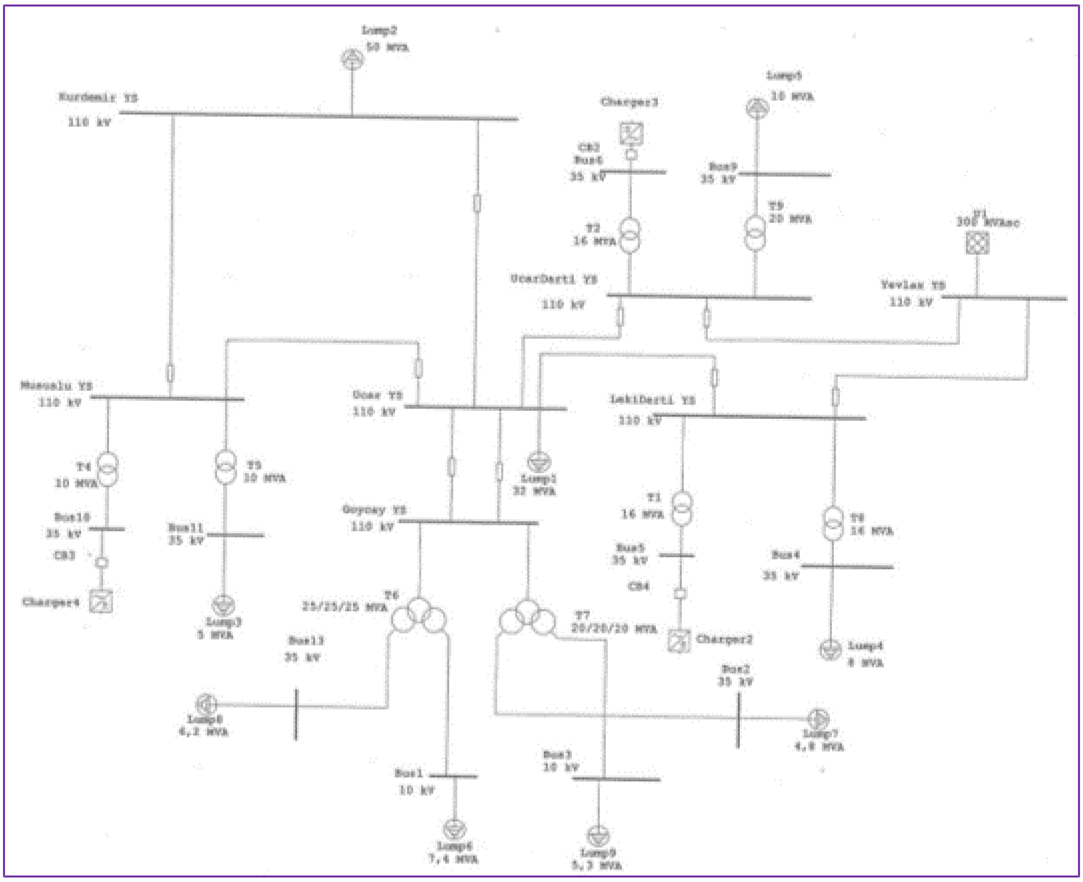


Figure 6. Fragment of the 110/35/10 kV network scheme of the energy system.

Musulli 110/10kV dart substation (2x10MVA) is connected to 110kV 2nd Sigirli line. The converter YS feeds the 6-phase rectifiers. In stage format, reports of settled modes were made for values of 10 and 20 MVA of the load. The reported results of the final harmonic ratio K_U (THD) of voltage in Goychay 110/35/10 kV YS buses are given in Figure 7 and Appendix 2. As you can see from the picture, maximum loads are obtained at nodes 1, 2, 4, 6, and 7, which is above the norm. Since some 110kV nodes are at the minimum value of the load, it is necessary to reduce the high harmonics of the voltage and to develop a special control algorithm of SCB in such conditions.

As can be seen in the diagram, the converter devices (semiconductor device rectifiers that convert alternating current to direct current) of the power station distort the sinusoidality of the voltage and current and demand a non-sinusoidal voltage from the power system. As a result, in the spectrum of the distorted supply voltage, in addition to the fundamental harmonic, high-frequency harmonics appear. These harmonics in the spectrum of current and voltage can penetrate into the electrical networks of the power system, causing additional power losses and at the same time causing malfunctions of relay protection devices. In addition, they have negative effects on the operating modes of network and consumer electrical equipment. There are problems in registering electricity with electricity meters. From this point of view, the management of reactive power compensation is considered by taking into account the non-sinusoidality of the voltage in the traction substation electric network.

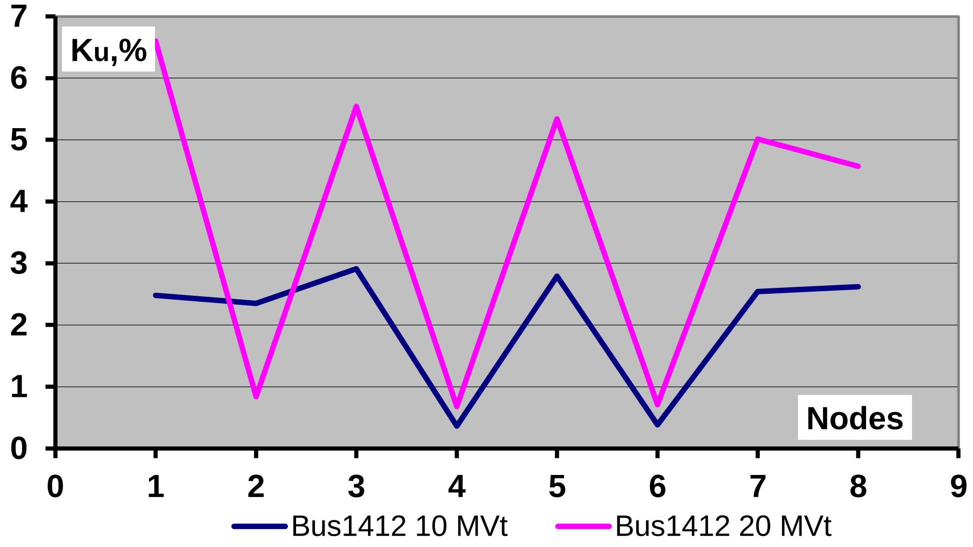


Figure 7. 110/35/10 kV Goychay according to the loads of traction substation values of the network THD per node

Figure 8 shows the values of the final harmonic complex coefficient for two values of the nonlinear load on the Ucar 110/35/10 kV network. As it can be seen, the values of the coefficient are 6.8% at the maximum value of the load at nodes 2, 4, 6, which exceeds the norm by 240%. At the minimum price of the load, this coefficient is 3.6% and is 80% higher than the norm.

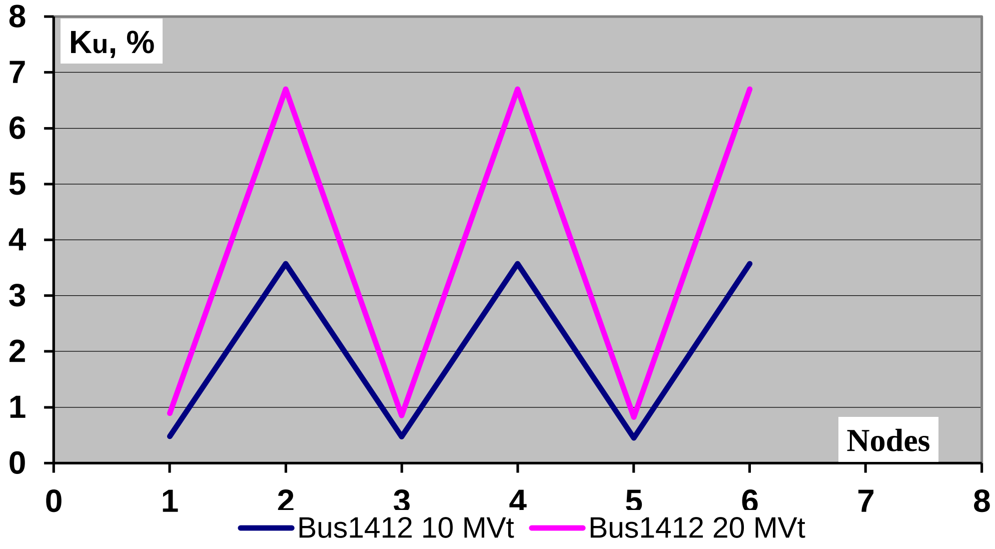


Figure 8. Ucar 110/35/10 kV according to traction substation loads values of the network THD per node

Figure 9 shows the profile of the coefficient for different connection variations of HHS to nodes B5, B6, B10 for individual nodes. As can be seen from the figure, the value of the final harmonic sum coefficient is around 20% at the minimum load where all three HHSs are connected, which is 18% higher than the norm (2%).

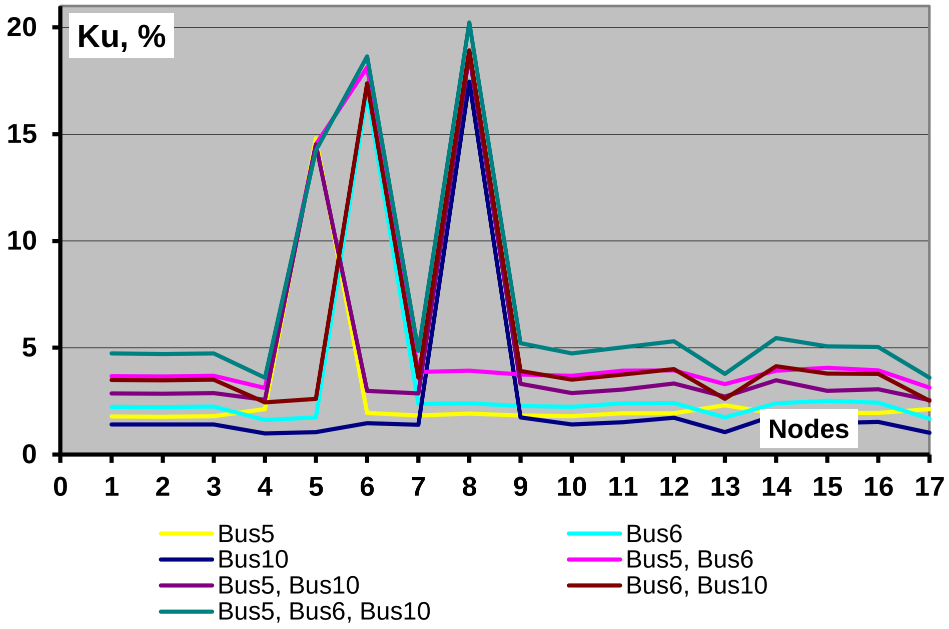


Figure 9. Minimal for the case of connecting HHS to nodes B5, B6, B10 profile of final harmonic sum coefficient at load

Thus, the conducted reports give reason to note that when working the reactive power compensation and its management algorithm under the conditions of specific loads, the final voltage should be adjusted to ensure frequent overloads of SKB and, accordingly, to prevent their premature failure. it is important to consider the values of the harmonic coefficient.

4. INTELLECTUAL CONTROL OF REACTIVE POWER WITH CONSIDERATION OF THE FINAL HARMONIC COMPOUNDING COEFFICIENT

Mamdani algorithm was selected as decision making algorithm. This algorithm is often used in practice, as it is better at solving many management problems in real time. For this, it is possible to create a fuzzy approximation between the input and output quantities by using the following well-known fuzzy linguistic model:

$$\begin{gathered} if\ x_i = A_{1j}\ and\ .....\ x_n = A_{nj}\ thend\ y_i = B_i \\ i = \overline{1,n} \quad and \quad j = \overline{1,m} \end{gathered} \tag{1}$$

Four types of membership functions were used in the work: triangular, trapezoidal, S and Z-shaped. They are expressed by the following formulas [16, 17]:

S-shaped. It is given by two parameters - a, b:

$$\mu(x)=\begin{cases}0, & x<a\\ \dfrac{x-a}{b-a}, & a<x<b\\ 1, & b<x\end{cases} \tag{2}$$

Z-shaped. It is given by two parameters - b, c:

$$\mu(x)=\begin{cases}1, & x<b\\ \dfrac{c-x}{c-b}, & b<x<c\\ 0, & c<x\end{cases} \tag{3}$$

Triangular. It is given with three parameters - a, b, c:

$$\mu(x)=\begin{cases}0, & x<a\\ \dfrac{x-a}{b-a}, & a<x<b\\ \dfrac{c-x}{c-b}, & b<x<c\\ 0, & c<x\end{cases} \tag{4}$$

Trapezoidal. It comes with four parameters - a, b_1, b_2, c:

$$\mu(x)=\begin{cases}0, & x<a\\ \dfrac{x-a}{b_1-a}, & a<x<b_1\\ \dfrac{c-x}{c-b_2}, & b_2<x<c\\ 0, & c<x\end{cases} \tag{5}$$

Figure 10 shows the structure of synthesized fuzzy decision making.

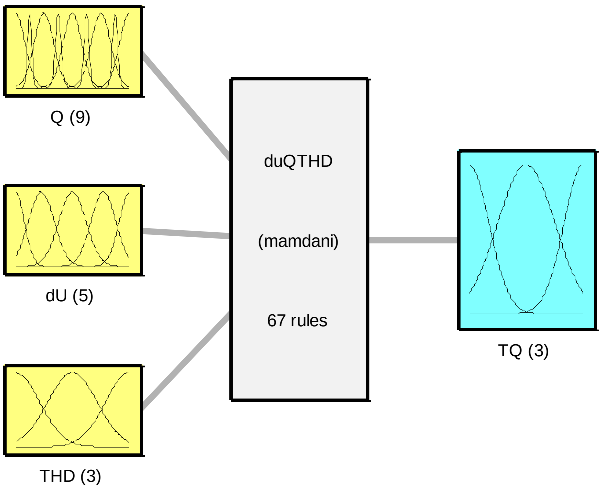


Figure 10. Structure of fuzzy logic decision making block

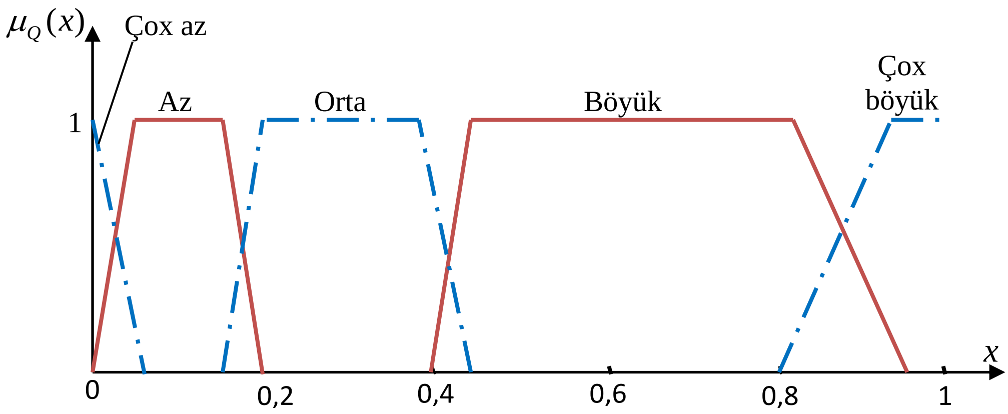


Figure 11. Fuzzy subsets of "Reactive power" variable

The use of the following linguistic variables is based on the operation of the fuzzy controller. The fuzzy subset of the reactive power linguistic variable is expressed $E_{1i}\ \ i=\overline{1,5}$ by fuzzy term-sets T(Q) as follows:

$$\left.\begin{array}{lll} E_{11}=VS & (\text{Very small}) & \underline{\underline{\Delta}}(\varepsilon,\mu_{11}(\varepsilon(Q))) \\ E_{12}=S & (Small) & \underline{\underline{\Delta}}(\varepsilon,\mu_{12}(\varepsilon(Q))) \\ E_{13}=M & (Medium) & \underline{\underline{\Delta}}(\varepsilon,\mu_{13}(\varepsilon(Q))) \\ E_{14}=B & (Big) & \underline{\underline{\Delta}}(\varepsilon,\mu_{14}(\varepsilon(Q))) \\ E_{15}=VB & (Very\,big) & \underline{\underline{\Delta}}(\varepsilon,\mu_{15}(\varepsilon(Q))) \end{array}\right] \tag{6}$$

The fuzzy values of this linguistic variable are as follows (Figure 11):
Very big – (0 0.05) parameter Z-shaped membership function;
Big - (0 0.05 0.15 0.2) parameter trapezoidal membership function;
Medium - trapezoidal membership function with parameter (0.15 0.2 0.4 0.45);
Small - trapezoidal membership function with parameter (0.4 0.45 0.85 0.95);
Very Small - (0.8 0.91 1) parameter S -shaped membership function.

Other linguistic variables "Dynamics", "Tension", "Harmonic Distortion", "Number" and "Direction" are written analogously. The following fuzzification and defuzzification operators are used for fuzzy logic inference [15]:

Оператор фаззификации:

$$F = fuzzifier(Q, Q', U, K_U, N) \tag{7}$$

Here Q, Q', U, K_U, N - clear signals entering the system; $F -$ fuzzy set; $fuzzifier -$ fuzzification operator.

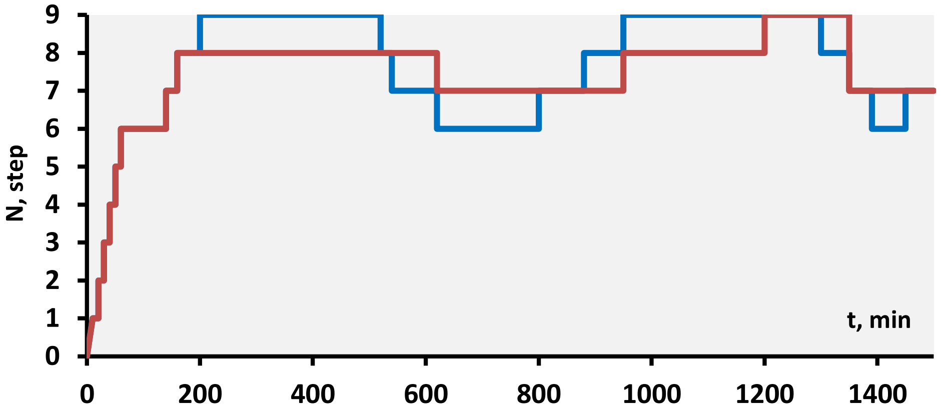
Defuzzification operator:

$$Y = F^{-1}(\mu_i(Y^*)) \tag{8}$$

here $Y-$ vector of clear control actions; $F^{-1}(\cdot)-$ defuzzification operator; $Y^{*}-$ vector of resulting fuzzy control actions; $\mu_i(\cdot)-$ the resulting membership function of control actions.

Figure 12 shows the operational diagram of the capacitor unit after reactive power compensation and control. As can be seen from the figure, the reactive load demand varies in the range of 250-490 kVAr. After the control, the reactive power received from the network is approximately 30-40 kVAr, and in some cases does not exceed 100 kVAr. The number of cycles of capacitor sections is equal to 19. This is lower than the traditional regulation.

Thus, the proposed intelligent control system based on the fuzzy controller performs a small number of conversions and increases the reliability of the operation of the switching devices that convert these capacitor bank steps. The device is resistant to obstacles, has a robust response to parametric effects, is quick-acting, has a wide adjustment range for reactive power, improves the efficiency of minimum electric power distribution in distribution networks, and can be used to control reactive power flows in real time in similar facilities.



b)

Figure 12. The reactive load of the demanders (a) and the steps performed (b) variation curves of the number of revolutions

5. CONCLUSION

1. In the conditions of non-sinusoidal voltage, for the purpose of development and practical implementation of the intelligent control algorithm of SKB, the report of the high harmonics of the voltage in the tires and the current in the arms was made according to the real PESH scheme of the energy system. The reports were made for the 110/35/10 kV grid circuit fragment of the energy system connected to Musulli, Ujar and Leki DYS from the 110 kV side. These converter substations send high harmonics into the grid, significantly degrading the quality of electricity.

2. An algorithm was proposed for intelligent control of reactive power based on Fuzzy Logic in the conditions of transformer substations and rapidly changing loads, which significantly affect the quality of voltage in the power grid. Another important feature of a fuzzy logic device is that it has relatively simple scalability. Adding new features and functionality to such devices is easy and inexpensive.

3. With a fuzzy control device, the regulation is obtained better, as the number of circuit changes decreases, the longevity of the capacitor battery increases and the probability of its failure decreases.

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An intelligent system for high-quality automated control of multi-connected technological processes in mechanical engineering

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DOI - 10.61413/NWSP6561

Absrtact.

The possibility of using the simplest methods of mathematical description of technological processes of engineering production as an object of automatic control, taking into account the multiply, delay, nonlinearity, stochasticity, as well as the synthesis of the corresponding ACS (automatic control systems) with high dynamic quality indicators.

Keywords: engineering production, production processes, control, multiply connected, delay, nonlinearity, stochasticity.

The relevance of the problem. A distinctive feature of many technological processes of machine-building production, as control objects, is their multidimensionality in the presence of interconnection between individual control channels, delays, various types of nonlinearities, and stochasticity.

An effective solution to the problem of high-quality management of such objects is feasible only using the capabilities of intelligent automatic control systems (IACS) with the creation of an appropriate Database (DB), Knowledge Base (KB) and Decision Block (DB).

Problem statement Analysis of some aspects of multicommunication, certain types of nonlinearities and stochasticity in technological processes of machine-building production as control objects, as well as appropriate methods of structural and parametric synthesis of ACS, providing higher dynamic quality indicators.

Solution of the problem. In this statement of the problem, the problem of identification, i.e. structural and parametric synthesis of mathematical models (MM) of individual control channels and disturbances of the control objects under consideration, comes to the fore. Here, within the framework of a deterministic and linearized approach, the problem arises of making a decision on the structural and parametric approximation of MM technological processes and technical devices, for example, electric, pneumatic or hydraulic motors, as well as, in general, drives of metal-cutting machines, industrial robots and other equipment with differential equations of minimal order, ordinary or with a delayed argument.

In the aspect of multicommunication, the problem arises of choosing various alternative topological models of "natural" relationships between individual separate channels of control objects (CO) with subsequent decision-making on the organization of "artificial" relationships, either compensating for the first (with the autonomy of local ACS), or reinforcing them (with coordinated management) [1,2].

Figure 1 shows an example of two possible options for organizing compensating effects in the presence of unidirectional relationships between the separate (local) i-m and j-m circuits of ACS, which take place, for example, in continuous thermal furnaces. Here W^o_{ii}, W^o_{jj} and W^o_{ji}, respectively, are the transfer functions (TF) of the "direct" connections of the separate channels of the CO and the "cross" connection between them; W^{p}_{ii} and W^{p}_{jj} are the TF of local regulators; g_i and g_j are given, and y_i and y_j are the actual values of the controlled quantities; u_{ii} and u_{jj} are the control ones, and f_i and f_j are the disturbing effects in the control channels. Dotted and dash-dotted lines represent alternative options for "artificial" connections that eliminate (compensate) the influence of i of local ACS on the j. In one case, a compensating regulator W^{kp}_{ji} is synthesized, and in the second, a compensating device W^{ky}_{ji}, the final choice of which is also determined by the technical implementation.

The structure and parameters of the TF of required connections can be found based on the condition of invariance (independence) of the controlled quantity y_j from the control action u_{ii}.

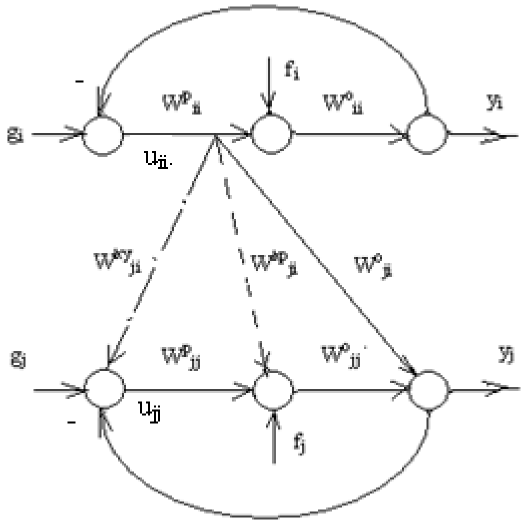

Fig. 1. An example of alternative compensation for unidirectional interconnection between separate channels

For the first and second options, the specified condition will be written as:

$$y_j= u_{ii}(W^{o}_{ji}- W^{\text{кр}}_{ji} W^{o}_{jj})=0 \quad \text{and} \quad y_j= u_{ii}(W^{o}_{ji}- W^{\text{ку}}_{ji} W^{\text{кр}}_{jj} W^{o}_{jj})=0 \qquad (1)$$

Taking into account the inequality of the control action to zero (the conditions of invariance will take the form:

$$(W^{o}_{ji}-W^{\text{кр}}_{ji} W^{o}_{jj})=0 \quad \text{and} \quad (W^{o}_{ji}-W^{\text{ку}}_{ji} W^{p}_{jj} W^{o}_{jj})=0 \qquad (2)$$

from where we get the TF of the compensating regulator and the compensating device.

$$W^{\text{кр}}_{ji} = W^{o}_{ji} \; / \; W^{o}_{ji} \;, \quad W^{ky}_{ji}= W^{o}_{ji}/ W^{p}_{jj} W^{o}_{jj} \qquad (3)$$

In a similar way, the problem is solved with two-way interconnections of separate CO channels.

The technological processes of heat treatment of mechanical engineering products are characterized by inertia and non-oscillation, which allows their mathematical description to use approximation by ordinary differential equations of the first order with a delayed argument [3]. For static and astatic control objects, such equations and TF in engineering calculations are usually presented in the form:

$$T_o dy(t)/dt + y(t) = K_o x(t - \tau_o), \qquad (4)$$

and $$dy(t)/dt = K_o x(t - \tau_o), \qquad (5)$$

or $$T_o dy(t)/dt = x(t - \tau_o), \ ) \qquad (6)$$

Here T_o is the time constant, K_o is the transmission coefficient, and τ_o is the time of net (transport) delay.

Engineering synthesis [3,5] of local ACS in such cases is associated with making a decision on choosing one of the typical linear control laws (I,P,PD,PI,PID), as well as one of the three types of transients offered in the "menu": aperiodic (with a minimum control time-t_p=min), with a 20% overshoot (with a minimum time of the first half-oscillation-t_{p1}=min) and with a minimum integral of the standard deviation (error)-= min. Then semi-empirical formulas are used to calculate the coefficients of the corresponding adjustment of the regulators (proportional, differential and integral components) according to the previously identified K_o, T_o and τ_o control channels of the CO.

From the environment of various kinds of nonlinearities, we will highlight the inherent in some technological processes of mechanical engineering (mechanical and heat treatment) as control objects - an abrupt change in static and dynamic parameters as a function of quantities and signs of controlled variables and control actions. In such cases, to improve the quality of transients, it seems natural to use control algorithms with switching parameters (coefficients) of control actions, which can be considered as the simplest class of variable-structure systems (VSS) [4].

The use of the latter, besides additional opportunities to improve the qualitative indicators of transients, also has the advantage of ensuring invariance to the unsteadiness of the CO and the action of disturbing influences (in the case of using sliding motion modes). For example, in the presence of non-linearities in the form of dependence of the parameters of the above-mentioned models of the CO on the sign of control actions (changing the direction of supply of the grinding wheel or workpiece, fuel consumption in gas furnaces of heat treatment, etc.):

$$K_0 = \begin{cases} K_{01} \text{ при } \operatorname{Sgn} U < 0 \\ K_{02} \text{ при } \operatorname{Sgn} U > 0 \end{cases}, \quad T_o = \begin{cases} T_{o1} \text{ при } \operatorname{Sgn} U < 0 \\ T_{o2} \text{ при } \operatorname{Sgn} U > 0 \end{cases}, \quad \tau_o = \begin{cases} \tau_{o1} \text{ при } \operatorname{Sgn} U < 0 \\ \tau_{o2} \text{ при } \operatorname{Sgn} U > 0 \end{cases} \qquad (7)$$

then in the simplest case – using the linear P (proportional) law of regulation - the corresponding empirical values of the proportionality coefficient of the regulator recommended in [3,5] can change similarly:

$$K_p = \begin{cases} K_{p1} \text{ при } \operatorname{Sgn} U < 0 \\ K_{p2} \text{ при } \operatorname{Sgn} U > 0 \end{cases}. \qquad (8)$$

However, when using VSS algorithms in this case, even in the switching mode, for example, in the form of

$$K_p = \begin{cases} K_{p1} \text{ при } \dot{\varepsilon} s < 0 \\ K_{p2} \text{ при } \dot{\varepsilon} s > 0 \end{cases}$$

, where

$$s = \dot{\varepsilon} + c\varepsilon \qquad (9)$$

It is possible to significantly improve the quality of transients by choosing K_{p1} equal to the recommended one for oscillatory c = min, and K_{p2} for aperiodic transients. It should be noted, however, that in this case, quasi-sliding movements (with finite amplitudes and frequencies) take place when choosing the sliding mode.

A number of disturbing influences inherent in the technological processes of machine-building production as objects of management are random. Examples may be the micro-roughness (roughness) of the surface of workpieces in metal cutting processes, vibrations of the MDTP system (machine-device-tool-part), etc. Therefore, the identification of such channels and the corresponding synthesis of the control part in order to reduce or completely eliminate the negative impact of such on the quality of products, reliability of cutting tools and equipment becomes an integral part of an intelligent ACS.

In the simplest and most common case, such random processes in a certain range of changes in the quantities under consideration, for example, the above-mentioned surface roughness of the workpiece *x(t)* and the machined (turning, milling, grinding, etc.) parts *y(t)* can be considered stationary (when their set averages are equal to the time averages-ergodic hypothesis [1]), so that the identification of the corresponding channels can be carried out on the basis of autocorrelation functions (ACF) - $R_{xx}(\tau)$,$R_{yy}(\tau)$ - and cross correlation functions (CCF)- $R_{xy}(\tau)$, $R_{yx}(\tau)$, determined by individual implementations of stochastic processes. For centered values $\overset{0}{x} = x - \bar{x}$; $\overset{0}{y} = y - \bar{y}$, where $\bar{x}$, $\bar{y}$ are the average values of the variables the corresponding expressions have the form:

$$R_x(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \overset{0}{x}(t)\, \overset{0}{x}(t+\tau)dt,\ R_y(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \overset{0}{y}(t)\, \overset{0}{y}(t+\tau)dt,$$

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \overset{0}{x}(t)\, \overset{0}{y}(t+\tau)dt \qquad (10)$$

Here, *T* is the duration of integration (observation) of random processes.

Fig. 2 shows examples of typical ACFs of random processes, one of which (Fig. 2,b) attenuates vibrationally, which indicates the presence of a periodic component in the random process associated, for example, with shape deviations, undulation, etc. of the workpiece during cutting.

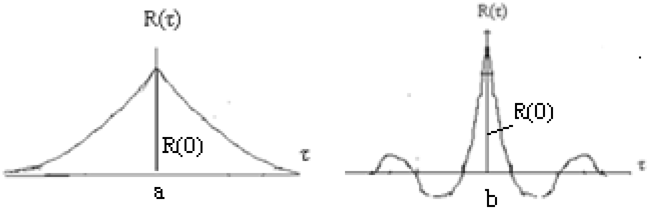

Fig.2. Examples of typical ACFs of random processes

The construction of the MM stochastic channel *x(t) - y(t)* according to their ACF and CCF is possible using the auto- and interspectral densities - $S_{xx}(\omega)$-(ASP) and $S_{xy}(\omega)$-(VSP) obtained from the former using direct Fourier transforms:

$$S_x(\omega) = \int_{-\infty}^{\infty} R_x(\tau) e^{-j\omega\tau} d\tau ; \qquad S_y(\omega) = \int_{-\infty}^{\infty} R_y(\tau) e^{-j\omega\tau} d\tau$$

$$S_{xy}(i\omega) = \int_{-\infty}^{\infty} R_{xy}(\tau) e^{-j\omega\tau} d\omega \qquad (11)$$

The analytical expressions of monotonic (10) and oscillatory ACF (11), as well as their corresponding ASF, are presented below, and in Fig. 3 graphs of the latter:

$$S(\omega) = \qquad (12)$$

$$= R(0) \quad ; \quad S(\omega) = \qquad (13)$$

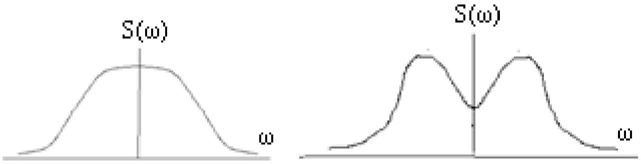

Fig.3. Graphs of ASF corresponding to monotonous oscillatory ACF

MM of stochastic channels in the form of AFC (amplitude-frequency characteristics) and APFC (amplitude-phase-frequency characteristics) determined by AFS and VSF are given in (12).

$$|W(j\omega)| = \sqrt{\frac{S_y(j\omega)}{S_x(\omega)}} \quad \text{and} \quad W(j\omega) = \frac{S_{xy}(j\omega)}{S_x(\omega)} \qquad (14)$$

The presence of MM stochastic channels makes it possible, in particular, to synthesize compensating devices or regulators by using a combined control principle and invariance conditions, similar to how it was implemented above for cross-linking between separate MACS channels.

Conclusion

The paper examines the problem of structural and parametric synthesis of mathematical models of interconnected technological processes, in particular, machine-building production, as control objects, as well as the corresponding control part in order to ensure high quality control indicators, taking into account the presence of certain types of nonlinearities, delay and stochasticity. An effective solution to such a problem is advisable within the framework of intelligent automatic control systems (ACS).

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METHOD FOR ASSESSING ELECTRICITY LOSSES IN PROBLEMS OF ON-LINE OPTIMIZATION OF POWER SYSTEM MODES

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DOI - 10.61413/BVOP4459

Abstract: In operational management, the optimization of power distribution is the process of adjusting the regime for active power, obtained during its short-term planning and optimization.During the operational optimization of the regime, unscheduled power between stations must be distributed in such a way as to ensure the same relative increases in energy consumption at power plant units, taking into account the relative increases in power losses in the network from the power of these stations. The article considers a method for the operational assessment of the relative increments of power losses for the tasks of operational optimization of the mode by active power.

Keywords: Power system, power loss, power plant.

1. INTRODUCTION

Operational optimization of load distribution in a mixed power system has a number of features, both in terms of the sequence of algorithmic constructions, and in terms of software implementation of the developed algorithms. The possible participation of HPPs in covering unscheduled capacity necessitates operational optimization of the regime, taking into account the efficient use of water resources in the energy system, and should be carried out according to the criterion of minimum energy consumption at power plants participating in covering this capacity. In this case, it is especially difficult to estimate the relative increase in power losses, since the relative increase in power losses from the power of power plants changes both when the network scheme changes and when the operation parameters change [1].

2.ESTIMATION OF THE RELATIVE GROWTH OF POWER LOSSES

In operational management, the optimization of active power distribution is the process of adjusting the regime for active power obtained during its short-term planning [2-4]. As with short-term planning, in a hydrothermal power system with operational control, the equation for the optimal distribution of active capacities between power plants is the equation:

$$\frac{b_1}{1-\sigma_1} = \lambda_a \frac{q_a}{1-\sigma_a} = \lambda_b \frac{q_b}{1-\sigma_b} = \cdots = \lambda_n \frac{q_n}{1-\sigma_n} \qquad (1)$$

The operational optimization algorithm consists in the implementation of the mode re-optimization equation (1) for active power.

In contrast to short-term planning, with operational optimization of the regime for active power, the optimization equation is characterized as follows: when the regime changes, unplanned power between stations must be distributed in such a way as to ensure the same relative increases in energy consumption at power plant units, taking into account the relative increases in power losses in the network from power these stations. At the same time, taking into account the relative increases in power losses from the power of power plants is a correction of the relative increases in energy consumption at the corresponding power plants. To implement the principle of optimality, it is necessary to quickly estimate the power losses and the relative increases in active power losses in the network.

An operational assessment of the relative increments of active power losses in the network is carried out either on the basis of the current values of the power of power plants or voltages in controlled nodes, and are found either by regression equations or by the method of average voltages.

3. CONSTRUCTION OF ANALYTICAL CHARACTERISTICS OF RELATIVE INCREMENTS OF ACTIVE POWER LOSSES IN ELECTRICAL NETWORKS BY NODE VOLTAGE VECTORS

In operational management, to determine the relative growth of power losses in the power system, telemetry of source voltage vectors can be used without introducing data on the parameters of the electrical network, loads of power plants and consumers into the calculations [5-6].

As is known, in the general case for heterogeneous networks.

$$\sigma_i^P + \vartheta_i^Q = \frac{2\,(U_1 - U_0)}{U} \qquad (2)$$

$$\sigma_i^Q - \vartheta_i^P = 2\sin\delta_i \qquad (3)$$

Where,

σ_i^P, σ_i^Q, ϑ_i^P, ϑ_i^Q – relative increments of active power losses by source active power, relative gains of active power by source reactive power, relative increments of reactive power losses by source active power and relative increments of reactive power losses by source reactive power, respectively, U_i- source voltage, U_0 - balancing node voltage, U is the average network voltage, σ_i is the angle between the voltage vectors of the sources and the balancing nodes.

In the general case, these equations are not enough to determine the relative power losses, since the number of unknowns is greater than the number of equations. For an approximate solution of these equations, we first neglect the inhomogeneity of the network, when the quality factor of all branches is assumed to be the same, i.e.

$$\psi_s = arctg\frac{x_s}{r_s} = idem \qquad (4)$$

Then, taking into account

$$\vartheta_i^p = -\,\sigma_i^P\, tg\psi \qquad (5)$$

$$\vartheta_i^Q = -\sigma_i^Q tg\psi \qquad (6)$$

Equations (2) and (3) will take the form:

$$\sigma_i^p - \sigma_i^Q tg\psi = \frac{2(U_i - U_0)}{U} \qquad (7)$$

$$\sigma_i^Q + \sigma_i^P tg\psi = 2\sin\delta_i \qquad (8)$$

By solving equations (7), (8) we obtain the following formulas for the relative gains in active power losses:

$$\sigma_i^p = \frac{2(U_i - U_0)}{U} \cos^2\psi + \sin\delta_1 \sin 2\psi \qquad (9)$$

$$\sigma_i^Q = \frac{-(U_i - U_0)}{U} \sin 2\psi + 2\sin\delta_1 \cos^2\psi \qquad (10)$$

And if we neglect the difference in the phase angles of the power of the nodes, then $tg\varphi_i = \frac{Q_i}{P_i}$, will be the same for all nodes, and then there will be the following relations between the relative gains in losses: $\sigma_i^Q = \sigma_i^p tg\varphi$ and $\vartheta_i^Q = \vartheta_i^P tg\varphi$

In this case, equations (2) and (3) will take the following form:

$$\sigma_i^p + \vartheta_i^P tg\varphi = \frac{2(U_i - U_0)}{U} \qquad (11)$$

$$\sigma_i^p tg\varphi - \vartheta_i^P = 2\sin\delta_i \qquad (12)$$

By solving equations (11) and (12), we obtain the following equations for relative loss increments:

$$\sigma_i^p = \frac{2(U_i - U_0)}{U} \cos^2\varphi + \sin\delta_1 \sin 2\varphi \qquad (13)$$

$$\sigma_i^Q = \frac{(U_i - U_0)}{U} \sin 2\varphi + 2\sin\delta_1 \sin^2\psi \qquad (14)$$

As can be seen from Figure 1, the sum of the right and left parts of equations (9) and (10) for different values of the quality factor of all branches is a band of possible solutions limited between $tg\psi_{max}$and $tg\psi_{min}$on the voltage plane and an increase in active power losses[7-10].

And the sum of the right and left parts of the equation (13) and (14) at different values of the phase angles of power is a band of possible solutions limited between $tg\varphi_{max}$and $tg\varphi_{min}$on the voltage plane and increase in active power losses.

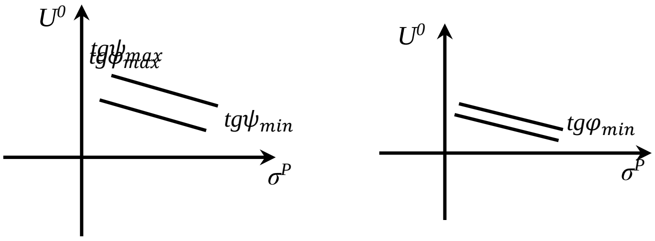

Fig. 1.a) The dependence of σ^P on voltage at the same quality factors of the branches
b) The dependence of σ^P on voltage at the same phase angles of power in the nodes

Adding the left and right parts of equations (9), (10), (13), (14) and dividing by 2, we obtain the equations for the relative increments of active power losses in the network for two averaged parameters.

$$\sigma_\iota = \frac{(U_i - U_0)}{U}(2cos^2\psi + 2cos^2\varphi - sin2\psi + sin2\varphi)$$

$$sin\delta_1\ (sin2\psi + sin2\varphi + 2cos^2\psi + 2sin^2\varphi) \qquad (15)$$

Equation (15) is a combination of two graphs shown in fig. 1 and therefore the boundary of possible changes in the relative increments of losses becomes even narrower and therefore the accuracy of the calculations increases. Let us denote the coefficients of two variables $\frac{(U_i - U_0)}{U}$, sinδ$_1$,, inside the brackets, respectively, *A* and *B*, then equation (15) will take the form:

$$\sigma_\iota = A\frac{(U_i - U_0)}{U} + Bsin\delta_1 \qquad (16)$$

The relative increase in active power losses is obtained as a function of two variables $\frac{(U_i - U_0)}{U}$ and $sin\delta 1$, U_i and U_0 are the voltages of the source and the balancing node, they are usually maintained at the nominal value, telemetered and can be used at the pace of the control process.

It should be noted that the resulting equation can be used for operational control if the coefficients for two variables $\frac{(U_i - U_0)}{U}$and $sin\delta_1$ are determined from preliminary calculations, since it is not possible to determine the components of the equation inside the brackets at the pace of the process. To obtain a working formula for a quick assessment of the relative increase in power losses, it is necessary to calculate a number of characteristic modes of the power system with the determination of the coefficients *A* and *B* in equation 16, and also determine *U* - the average voltage of the network. The fact is that the use of the *U*-average voltage of the network is difficult because usually the voltage telemetry contains significant measurement errors. Therefore, to determine the average network voltage, one can use the regression dependences of the average voltage as a function of the voltage of some nodes. To determine these nodes, it is possible to carry out steady state calculations for normal and post-accident modes with the determination of the nodes on the voltage of which the mains voltage mode depends to the greatest extent, the so-called sensor nodes. The voltage of these nodes can be taken as factors for determining the average network voltage.

To determine the coefficients *A* and *B*, calculations were made for some characteristic modes of the Azerenerji energy system. The results of calculations with the determination of the coefficients *A* and *B* are given below:

Table 1. Percentages, based on the rules of the membership functions

№	A	B
1	0.0021	0.172
2	0.0025	0.165
3	0.0022	0.167
4	0.0024	0.169
5	0.0023	0.168

It can be seen from the table that coefficient *A* changes in ten-thousand digits, and *B* - in thousandth digits, so the arithmetic average value will correspond quite accurately to the desired coefficients:

$A_{vr.}$= 0.0023, $V_{av.}$= 0.168 and equation (16) will take the form:

$$\sigma_{\iota} = 0.0023\,\frac{(U_i - U_0)}{U} + 0.168\sin\delta_1 \qquad (17)$$

To determine *U* - the average voltage of the network as a function of the voltages of some nodes, calculations of normal modes and post-emergency modes were carried out in the Azerenergy system, obtained by typical outages of some power lines, a total of 64 calculations. As a result, 7 nodes were identified, on the voltage of which the mains voltage mode depends to the greatest extent, the so-called sensor nodes. The voltages of these nodes were determined as factors for determining the average network voltage. Below, without details, the found regression coefficients for the mean stress are given.

$$U = 121 + 0.7722\,U_{HOV} + 0.4930\,U_{MUSH} + 0.5923\,U_{KHUR} + 0.2215\,U_{MAS} + 0.4622\,U_{AKSU} + 0.2123\,U_{AGC} + 0.3311\,U_{AGS} \qquad (18)$$

In this case, the standard deviation (SD) at the experimental points is 0.7%, and in the basic modes, when all factors are taken at an average level, the SD is 1.5%, which is at the level of the error in measuring telemetered node voltages. Thus, according to the telemetered values of the voltages of the sources, the balancing node and the 7 nodes listed above, it is possible to determine the relative increases in power losses in the network at the pace of the process.

Numerous calculations of the relative increases in power losses by the voltage vectors of the nodes show that the error for the minimum and maximum modes is greater (8%) than for the typical average modes (5%), when operational optimization of the modes by active power is possible.

4. CONCLUSIONS

1. In operational management, in order to optimize the regime, an estimate of the relative increase in power losses can be determined from the voltage vectors of the nodes.

2. Estimation of the relative increments of power losses by voltage vectors for the maximum and minimum modes, when the modes are forced modes, and for these modes operational optimization is usually not performed, has a large error.

3. For medium modes, when on-line optimization of the mode is possible, the estimation of the relative increase in power losses by the nodal voltage method has a smaller error, and therefore the voltage-based method is preferable for on-line optimization problems.

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SYNTHESIS OF SECOND-ORDER INVARIANT CONTROL SYSTEMS

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DOI - 10.61413/EZWN6336

Abstract. In this paper, to ensure invariance, the estimate of external perturbation is not used. An increase to a sufficient value of the gain of the controller and the identifier does not lead to a violation of the stability of the system. allows to achieve high speed and tracking accuracy of the reference trajectory.

Keywords. Invariant control systems; until sufficient estimation of the perturbation; Lyapunov function; quadratic function; observer.

Introduction. The article is devoted to the synthesis and research of control systems with a large amplification factor. A new solution of this type of systems is provided based on the Lyapunov function method. When using the Lyapunov function method, the control strategy is based on the condition that the time derivative of the Lyapunov function is less than zero.

The basis of the article is a new synthesis method based on the Lyapunov function of control systems with a large amplification factor. Since the equation of the system does not include the parameters of the object and external influences, the motion of the system is widely fully invariant. However, since the required quality indicators and stability reserves are limited in applied issues, it is possible to provide these indicators at a finite value of the amplification factor.

Based on analytical and computer studies, it is possible to determine the shortcomings of existing management systems and algorithms. In the indicated direction, a single-circuit structure of the control system was proposed, which allows to increase the amplification factor excessively without breaking the stability, which is the primary issue.

Main part. Invariant control systems against external excitations are considered more efficient in practical applications. G. V. Shipanov, who laid the foundation of the idea of invariance, tried to obtain the condition of absolute invariance due to the internal relations of the system [1].

A little later B.N. Petrov showed in his principle that to realize the principle of invariance, it is necessary to measure the excitatory effects [2]. The problem of measuring nonlinear non-stationary signals is well known. In some cases, it is possible to use it indirectly by measuring the compensatory variables that characterize the external excitatory effects [3].

The article proposes a method of constructing invariant control systems due to external excitations by evaluating the excitations.

Using the Utkin-Drajonovich equivalent control method allows you to get the following distinguishing features:

1. Infinitely increasing the amplification factor of the regulator and the observer does not lead to a violation of the stability of the system. It achieves high speed and accuracy. In many other works, methods of infinitely increasing the amplification factor of the open system have been proposed [4, 5].
2. Internal coordinates (state variables) of the systems are used to evaluate the excitation effects. In addition, when the transfer function of the object changes, it is not necessary to rebuild the

compensator due to the excitation effect channel. That is why, in contrast to known methods, the system proposed in the work is called the second order invariant system [6, 7, 8].
Consider the problem of stabilizing a oscillating object for simulation modeling:

$$\ddot{\boldsymbol{y}} = -\mathbf{0.5}\dot{\boldsymbol{y}} - \boldsymbol{y} + \mathbf{2}\boldsymbol{u} + \tilde{\boldsymbol{\phi}}(\boldsymbol{t}) \ ,$$

where,

$$f(t,y) = -0.5\dot{y} - y,\ b = 2,$$

$$\tilde{\phi}(t) = \phi(t) + 0.4\dot{\phi}(t),\ \phi(t) = sin(\,10t),$$

$$y_d(t) = 1(t).$$

Object transfer function:

$$W_u = \frac{2}{s^2 + 0.5s + 1}, \quad W_f = \frac{0.4s + 1}{s^2 + 0.5s + 1}.$$

The transfer function of the compensator:

$$W_u = \frac{W_f}{W_u} = \frac{0.4s + 1}{2} \approx \frac{0.205s + 0.5}{0.01s + 1}.$$

A PID controller is used to ensure the invariance of the system:

$$W_p = \frac{k_p s^2 + k_i s + k_d}{s}.$$

Figure 1 shows the structural diagram of the invariant control system implemented in the Matlab/Simulink software package.

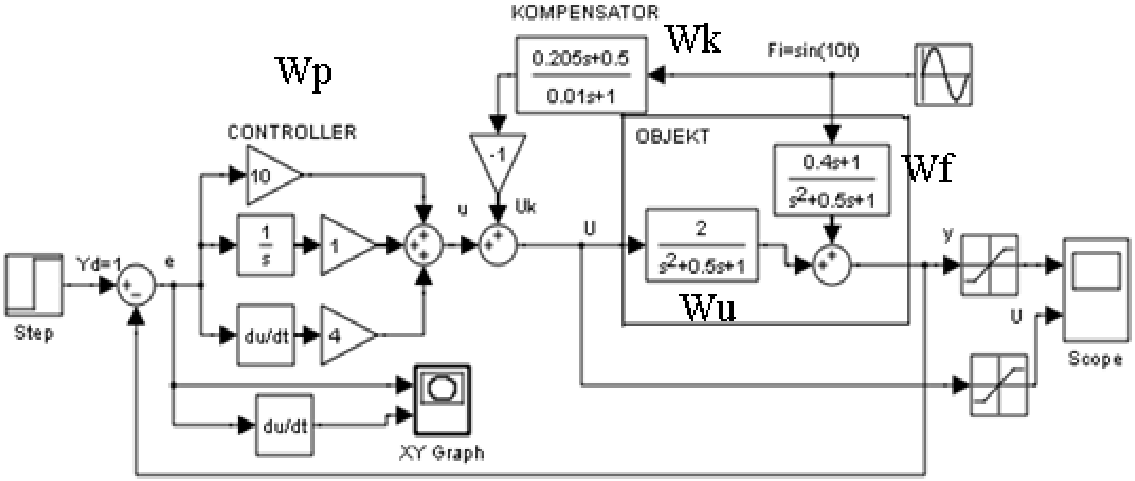
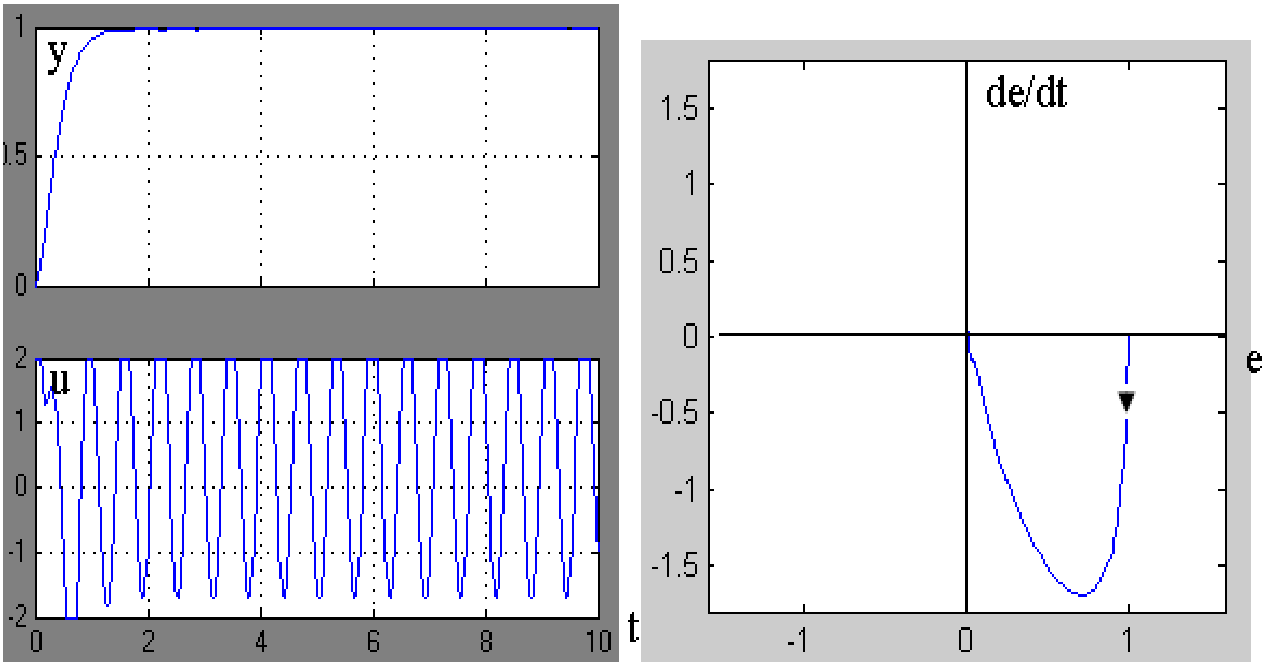


Figure 1. Structural diagram of the invariant control system

Controlled y(t), control u(t) signals (a), and phase portraits of the system (b) in Fig. 2, a-b shown. The tuning parameters were adopted as follows:

$$k_p = 10, k_i = 1, k_d = 4.$$

As can be seen, the harmonic external excitation effect is completely eliminated in the output.



a) b)

Figure 2. Dynamic characteristics of the system

Figure 3 shows the structural scheme of the proposed invariant system. Here,

$$u_{eq} = -0.5(c_1 e + \ddot{y}_d(t) + F(t)),$$

$$u_{st} = -0.5 k_p \cdot s(t).$$

$$c_1 = 4,\ N = 42,\ k_p = 16.$$

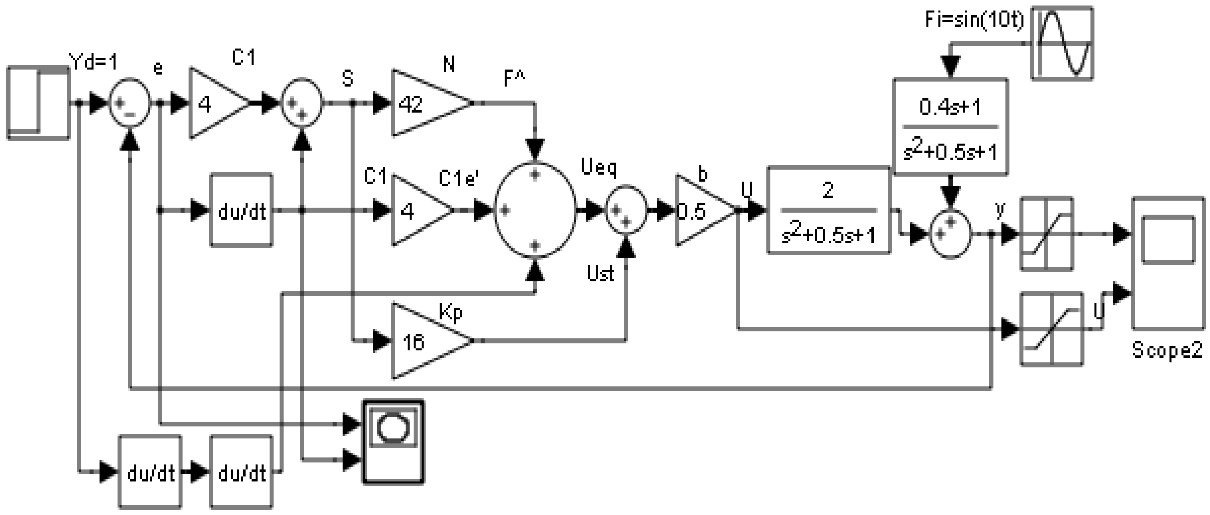
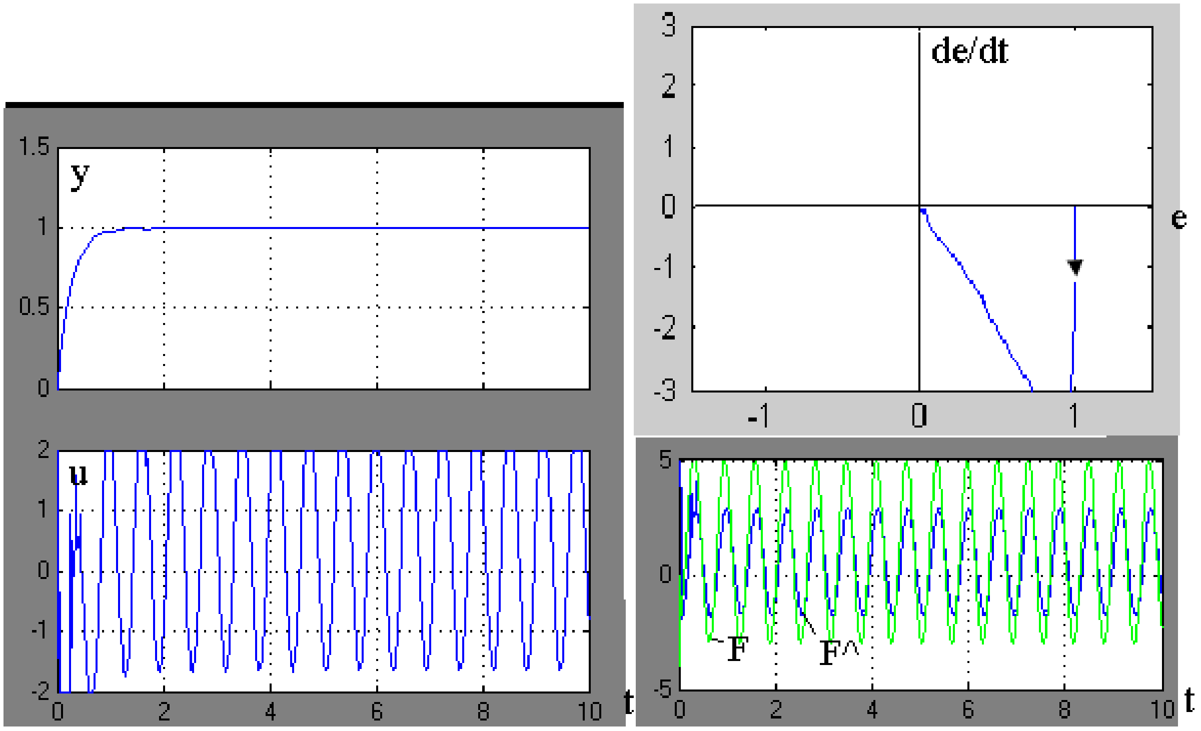


Figure 3. Structural diagram of the proposed invariant system

Figure 4, a-b shows the dynamic characteristics of the system.



a) b)

Figure 4. Dynamic characteristics of the system

Conclusion

Based on analytical and computer studies, the following main conclusions were obtained.

The shortcomings of the existing management systems and algorithms were analyzed, and as a result, the issues to be considered were determined. A single-loop structure of the control system, which is the primary issue in the indicated direction, which allows to increase the amplification factor without breaking the stability, and a method of ensuring invariance against uncontrolled external exciting effects, is proposed.

The efficiency and comparative analysis of the proposed methods and algorithms were evaluated by modeling and studying the test problems in Matlab/Simulink. The obtained positive results pave the way for the practical use of system technical analogs of Simulink schemes of synthesized control systems.

As it can be seen, the quality indicators of the transition characteristics y1(t) and y2(t) are almost the same, but in the second case the external excitation effect φ(t) is not measured.

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DISTRIBUTED SYSTEM FOR SOLUTION OF PLANNING AND CONTROL PROBLEMS IN POWER INTERCONNECTIONS

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DOI - 10.61413/SGHB8885

Abstarct. This paper presents the principles and foundations, on which construction and functioning of distributed system destined for optimal control of large power interconnections is based. Such power interconnections consist of power systems of independent countries and independent markets of electricity. Solution of optimization problems in large power systems according to these principles is carried out as coordinated solution of optimization problems of two levels: optimization problems of subsystems on lower level and optimization problem of upper level – determination of optimal power flows between subsystems. This organization of solution of optimal operation problems forms the basis for creation of efficient distributed control system providing global optimality of large power interconnections and self-determination of independent power systems. Hierarchical algorithm for solution of power flow problems, which can be implemented in this control system, is also presented in the paper.

Keywords: Parallel and Distributed Control Systems, Hierarchical Models, Large Power Systems, Power Flow, Optimal Power Flow.

1. INTRODUCTION

One of the most important problems in development of modern control systems for large power interconnections is that that they should provide for global optimality of functioning of these interconnections and at the same time ensure self-determination and conditions for internal optimality of decisions taken at the level of independent countries and local electricity markets. Existent organization of operation control system in these interconnections consisting of inde- pendent system operators, solving the problems of planning and dispatching in their own power systems and coordinating interchange of power and energy between power systems, makes it possible to achieve internal optimality of operation in each of power systems but cannot assure global optimality of functioning of these interconnections.

Practicable and most promising way for enhancement of economical efficiency in these interconnections lies in addition of one more layer to the existing structure of power systems control centers in UCTE, USA, Canada and CIS. The function of this upper layer should be calculation of optimal power flows between large power systems of these countries. Internal optimality of operation within power systems still will be provided by existing control centers of power systems.

Structure of distributed control system based on this concept and intended for realization of planning, dispatching and controlling functions in large power interconnections is presented on Fig.1. This system consists of lower layer computers, located in control centers of power systems and upper layer computer (server). Lower layer computers solve the problems of optimal control in power systems, whereas the upper layer computer determines values of optimal power flows between power systems.

This system realizes the principle of conservation of existing structure of control centers with addition to it of upper layer structure comprised of upper layer computer connected by communication channels with lower layer computers. This system is protected by Patents of Invention of Russian Federation and US. See [1] and [3].

Functioning of the distributed control system in solution of planning and control problems of large power system is based on the method of functional modeling (FM).

The main principles of the FM method, presented in [4] and [7] are as follows.

1. Representation of a technical system as a set of subsystems, adjoining each other in boundary nodes.
2. Building of a model as a hierarchical structure, consisting of interconnected systems of equations. In this structure subsystems are represented by lower level systems of equations. A higher level system of equations represents borders between subsystems (boundary nodes).
3. Representation of subsystems on the higher level of model by functional characteristics (FCs). FCs are input-output characteristics in which vectors of boundary variables of one kind are considered as input variables and boundary variables of another kind as output variables. These characteristics are obtained while meeting all constraints within subsystem.
4. Determination of the values of boundary variables on the higher level of the model through formation and solution of the system of connection equations (SCE), obtained from general expressions for boundary variables, pertaining to all boundary nodes.

Below it is shown how these principles are applied to solution of power flow and optimization problems.

2. HIERARCHICAL FM ALGORITHM FOR SOLUTION OF POWER FLOW PROBLEM

The FM algorithm for solution of a power flow consists of the following steps [6], [5],[4].

1. Setting of all voltages at internal nodes of subsystems to starting value.
2. Calculation of the voltages at boundary nodes, corresponding to the voltages at internal nodes set in the previous step.

Phase angles and voltage magnitudes at boundary nodes are calculated according to the following formulas

$$\begin{aligned} \theta_b &= arctg\frac{U_1\sin\theta_1+U_2\sin\theta_2}{U_1\cos\theta_1+U_2\cos\theta_2}, \\ U_b &= \frac{1}{2}\sqrt{U_1^2+U_2^2+2U_1U_2\cos\left(\theta_1-\theta_2\right)}, \end{aligned} \tag{1}$$

where indices 1 and 2 refer to internal nodes belonging to the same line as the boundary node b.

3. Calculation of the active and reactive power at each internal node of all subsystems. These values should be subtracted from the scheduled values and the resulting mismatches stored in a vector for each subsystem. (The next step should be taken only if these mismatches exceed a fixed number ε′.)
4. Check for completion of the iteration process.

On this step the fulfillment of the conditions

$$\begin{aligned} \max \Delta Pi &\le \varepsilon, \\ \max \Delta Qi &\le \varepsilon, \end{aligned} \tag{2}$$

is checked out.

5. Formation for each subsystem of a linear system of equations representing it on the first iteration and subsequent determination of the FC of subsystem from this linear system.

This linear system looks as follows

$$\left| \begin{array}{c} \Delta\dot{S}_i \\ \Delta\dot{S}_b \end{array} \right| = \left| \begin{array}{cc} A_{ii} & A_{ib} \\ A_{bi} & A_{bb} \end{array} \right| \left| \begin{array}{c} \Delta\dot{U}_i \\ \Delta\dot{U}_b \end{array} \right|, \tag{3}$$

where $\Delta\dot{S} = |\Delta P \Delta Q_1|^t$; $\Delta\dot{U} = |\Delta U \Delta\theta|^t$.

In (3) $\Delta\dot{S}_i$ is the vector of active and reactive power mismatches in internal nodes found on the previous step.

Applying the Gaussian elimination of internal variables to (3) we obtain

$$\left| \begin{array}{c} \Delta\dot{S}'_i \\ \Delta\dot{S}'_b \end{array} \right| = \left| \begin{array}{cc} A'_{ii} & A'_{ib} \\ 0 & A'_{bb} \end{array} \right| \left| \begin{array}{c} \Delta\dot{U}_i \\ \Delta\dot{U}_b \end{array} \right|. \tag{4}$$

The vector $\Delta\dot{S}_b$ in (3) should be set equal to zero before this elimination. Accordingly the vector in (4) is the vector of constant terms appearing in the place of this zero vector in the process of elimination.

From (4) follows that the FC of subsystem is

$$\Delta\dot{S}_b = A'_{bb}\Delta\dot{U}_b - \Delta\dot{S}'_b, \tag{5}$$

where $\Delta\dot{S}'_b$ variables is a vector of constant terms, $\Delta\dot{S}_b$ and $\Delta\dot{U}_b$ are considered as vectors of unknown

6. Formation and solution of the SCE, which is regarded as a higher level system of equations in this algorithm.

Formation of the SCE is executed in this algorithm by way of substitution of expressions in the right hand side of the FCs (5) into following system of equations for active and reactive powers crossing the boundary nodes

$$\Delta S_{bI} + \Delta S_{bK} = U. \tag{6}$$

Substitution of the expressions in the right hand side of (5) into (6) for all boundary nodes gives

$$A_s \Delta U_b^s = \Delta S_b^s. \tag{7}$$

Solution of this SCE gives values of increments of voltage angles and magnitudes in boundary nodes of subsystems.

7. Calculation of the increments of voltage angles and magnitudes in internal nodes of subsystems by substitution of subvectors of boundary variables found in previous step into equations (4) and performing backward Gaussian move in these equations.
8. Return to step (2)

3. HIERARCHICAL FM ALGORITHMS FOR SOLUTION OF OPTIMIZATION PROBLEMS

If the FM method is applied to solution of economic dispatch problem in large power system this system should be represented as a set of subsystems adjoining each other. If power flows through boundary nodes of subsystems are considered as boundary variables and there is only one boundary node between each pair of adjoining subsystems Lagrange function for this model can be constructed as a sum of Lagrange functions of subsystems in following form

$$L_s = \sum_I \sum_i F(P_{iI}) + \sum_I \left[\lambda_I \left(P_{LI} - \sum_{iI} P_{iI} + \sum_{bI} \pm P_{bI} \right) \right], \tag{8}$$

where P_{iI} is the power of the station i in the subsystem I , P_{bI} is the power flow through the boundary node b adjacent to the subsystem I, P_{LI} is the power consumed in the subsystem I.

Note that P_{bi} enters this function with sign + for one subsystem and sign – for adjacent subsystem.

Necessary condition for an extreme value of the objective function (8) can be obtained taking the first derivative of (8) with respect to each of the boundary variables and setting these derivatives equal to zero. It results in the following set of equations

$$\lambda_{Ib} - \lambda_{Jb} = 0 \qquad b = 1, \ldots, nb \,, \tag{9}$$

where index I_b denotes for one of subsystems adjacent to the boundary node b, and J_b denotes for another.

Each of equations in (9) applies to one of the boundary nodes between subsystems in this model and total number of these equations is equal to the number of these nodes.

The systems of internal equations, representing the minimum cost operating conditions for subsystem I if network losses are not taken into account look as follows

$$\frac{dF_{iI}}{dP_{iI}} - \lambda_I = 0, \tag{10}$$

$$P_{LI} - \sum_{iI} P_{iI} + \sum_{bI} \pm P_{bI} = 0. \tag{11}$$

Upper equations in this system are obtained from the condition that the first derivatives of the function (8) with respect to internal variables PiI should be equal to zero. Eq. (11) is the constraint equation of subsystem I (balance of power equation).

Finding expressions for the first derivatives of the cost functions of stations we can present Eq. (10) in explicit form

$$a_{iI} P_{iI} + b_{iI} - \lambda_I = 0. \tag{12}$$

In this case it is assumed for simplicity that the cost function has the form of a quadratic function.

Solution of the economic dispatch problem by the hierarchical FM algorithm consists of the following steps.

1. Formation of Eqs. (10), (11) and determination of the FCs of subsystems. Applying the Gaussian elimination of internal variables (i.e. P_{iI}) to the system (10), (11) for each of the subsystems the FCs of subsystems should be determined, having the following form

$$\lambda_I = a_I \sum_{bI} \pm P_{bI} + c_I. \tag{13}$$

2. Formation and solution of the SCE. Substituting for λIb and λJb from right-hand side of Eq.(13) for FCs of the subsystems I and J (adjoining to boundary node b) into Eq. (9) yields one of the equations, forming the SCE. In this way equations for all boundary nodes should be obtained. Set of these equations forms the SCE shown below

$$AP_b = b. \tag{14}$$

Solution of this linear system gives optimal values of power flows between subsystems.

3. Determination of power outputs of stations in subsystems. Substituting the values of optimal power flows on the borders of subsystems into Eq. (13) gives the values of Lagrange multipliers λI in subsystems. Then back substituting λI into Eq. (10) optimal power outputs of stations in subsystems should be found. These values are exactly the same that can be obtained by basic one level algorithms for solution of this problem.

Hierarchical algorithms of this type are now developed for all basic optimization algorithms.

4.DISTRIBUTED SYSTEM FOR DISPATCHING OF GENERATION IN LARGE POWER SYSTEMS

General structure of the FM algorithms and principles of the FM method constitute a ba- sis on which construction and functioning of distributed control systems intended for optimal control of large integrated electrical power systems can be founded. These large power systems (interconnections) consist of power systems of independent countries and independent markets of electricity. The most important problem, which should be solved in creation of such system is the necessity to combine in it on the one hand the ability to achieve global optimality of interconnection as a whole and on the other hand the ability to maintain self-determination and local optimality of power systems of independent countries. This problem can be solved in distributed control system having hierarchical structure and containing computers, belonging to different hierarchical levels of the system.

Figure 1 shows the configuration of this system.

In solution of power flow and optimal power flow problems (as well as other optimization problems) this system operates in each iteration in following way.

1. Formation of systems of equations for subsystems and determination of their FCs is executed concurrently by computers of lower level, placed within the limits of each subsystem.

Data on parameters of FCs of all subsystems are delivered from computers of lower level to computer of upper level (server).

2. Formation and solution of the SCE is executed by the computer of upper level. Data on the values of boundary variables are delivered to the computers of lower level.
3. Calculation of the values of internal variables of subsystems is executed concurrently by computers of lower level.

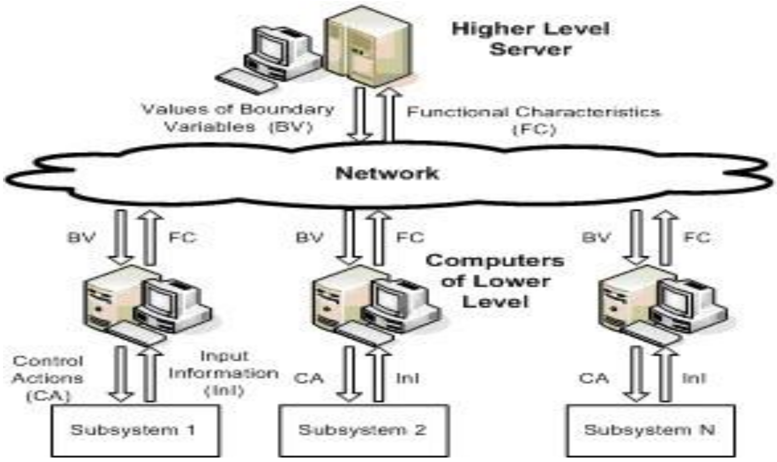

Figure 1. Configuration of the distributed control system.

Important features of this control system are the following.

1. All calculations on the lower level of the system are executed concurrently by computers of lower level.
2. Convergence of iteration processes in the algorithms working in this system is the same as in the corresponding basic algorithms.
3. Data delivery between computers in this system is limited to delivery of data on FCs and boundary variables. No data on internal parameters and internal state of subsystems of power system should be transferred from subsystems.

Optimal operation of large interconnections is based in this control system on coordinated solution of optimization problems of two levels: optimization problems of subsystems on lower level and optimization problem of upper level – determination of optimal power flows between subsystems.

This distributed system can be used not only for solution of optimization and control problems of large power systems but also for solution of power flow and state estimation problems in these systems if hierarchical FM algorithms are implemented for this purpose.

5. CONCLUSION

Hierarchical structure of the power system model described above corresponds to representation of large power interconnection as a set of interacting power systems (independent agents of upper level). By definition the FCs of subsystems (independent power systems) are input- output characteristics obtained while meeting all optimality equations and constraints within subsystems. From economical point of view these characteristics represent relationships between prices of energy (marginal costs) and amounts of energy traded between power systems when optimal control of generation within power systems is carried out.

When FCs of subsystems are known the SCE in hierarchical model can be formed. This upper level system of equations can be considered as mathematical formulation of the problem of determination of optimal power flows between power systems (problem of the market of markets) with inequality constraints taken into account.

This distributed system has following important advantages in comparison with existing decentralized control systems and possible traditional centralized control system.

1. Great reduction in total cost of energy generation necessary for supplying all consumers of electrical energy in European Interconnection because of optimal allocation of power production between the power stations within the European Interconnection.
2. Efficient organization of distributed computational process in the course of control problem solution, reduction of data transfer and enhanced reliability.
3. Self-sufficient solution of optimal control problems in power systems and at the same time optimal operation of interconnection as a whole.

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Contents

Yusifbayli N.A., Rustemzade E.Sh.

Innovative Energy Systems: The Role of Energy 4.0 in Shaping Azerbaijan’s Sector …......……..…2

Guliyev H.B.

Intelligent control of reactive power flows in power distribution networks, taking into account the influence of specific load…………………..…………......……..................................18

Farhadov V.G., Gasimov A.Y., Gojaeva A.B.

An intelligent system for high-quality automated control of multi-connected technological processes in mechanical engineering …………………………………………………….........…33

Nasibov V.Kh., Alizade R.R., Isgenderov E.C.

Method for assessing electricity losses in problems of on-line optimization of power system modes...40

Farhadov V.Q., Qasimov A.Y.

Synthesis of second-order invariant control systems…...………………..………....................……47

Soukhanov O.A.

Distributed system for solution of planning and control problems in power interconnections…….53